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Definition, Technology Readiness and Development Cost of the Orbit Transfer Vehicle Engine Integrated Control and Health Monitoring System Elements

By: I. Cannon, S. Balcer, M. Cochran, J. Klop, S. Peterson

Rocketdyne Division
Rockwell International

October 1991

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16. Abstract

An Integrated Control and Health Monitoring (ICHM) system was conceived for use on a 20Klb thrust baseline Orbit Transfer Vehicle (OTV) engine. Considered for space use, the ICHM was defined for reusability requirements for an OTV engine service free life of 20 missions, with 100 starts and a total engine operational time of 4 hours. Functions were derived by flowing down requirements from NASA guidelines, previous OTV engine or ICHM documents, and related contracts. The elements of an ICHM were identified and listed, and these elements were described in sufficient detail to allow estimation of their technology readiness levels. These elements were assessed in terms of technology readiness level, and supporting rationale for these assessments presented. The remaining cost for development of a minimal ICHM system to technology readiness level 6 was estimated. The estimates are within an accuracy range of plus or minus 20%. The cost estimates cover what is needed to prepare an ICHM system for use on a focussed testbed for an expander cycle engine, excluding support to the actual test firings.

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Rocketdyne Division, Rockwell International
6633 Canoga Ave., Canoga Park, CA. 91303

October 1991

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1.0 INTRODUCTION

The Integrated Control and Health Monitoring System (ICHM), provides comprehensive control and monitoring capabilities in support of overall Orbital Transfer Vehicle Engine (OTVE) mission requirements. The OTVE is considered for space-based missions including Lunar/Mars and orbital transfer. Such missions would include requirements for long duration space exposure, multiple, zero gravity engine starts, as well as the capability for deep throttling for landings. Reusability requirements dictate a service-free life of 20 missions, with 100 starts and a total engine operational time of 4 hours. The overall system life (with service) requirement is established as 100 missions, with 500 starts and engine operational time of 20 hours.
The ICHM system includes control and condition monitoring electronics, sensing elements, software/algorithms and effectors. Effectors are those components of the ICHM which are commanded by the controller electronics to operate the OTV engine. These include valve actuators, nozzle extension and gimballing actuators and igniters. An artists rendering of the 7.5Klb thrust OTVE is shown in Figure 1.

The ICHM system was conceived around the 20Klb thrust baseline OTV engine. This thrust level was selected because Rocketdyne had available power balance model data at off-design conditions of; 5% thrust, representative of 20:1 throttling (at mixture ratio 6:1), and full thrust at a mixture ratio of 5:1. Power balance model data at the on-design condition of 20Klb thrust at a mixture ratio of 6:1 was also used. The overall ICHM definition was not impacted by the use of the 20Klb thrust baseline, and only a minor effector change (igniter style) would be considered to adapt the ICHM results to the 7.5Klb version of the OTVE. The alternate igniter was considered in the identification of ICHM elements, and the related cost estimate. The schematic diagram of this OTVE configuration is shown in Figure 2.

Task E6, "Technical Readiness and Development Costs", entailed the definition of the ICHM system for the OTV engine. The minimal ICHM system was derived from a flowdown of engine requirements into system functions which, evaluated, and translated into a minimal set of ICHM elements (sensors, actuators, electronics, and software) to meet requirements with maximal technology readiness. A baseline design for each of these elements was described in enough detail to estimate the technology readiness and development costs of the minimal system.

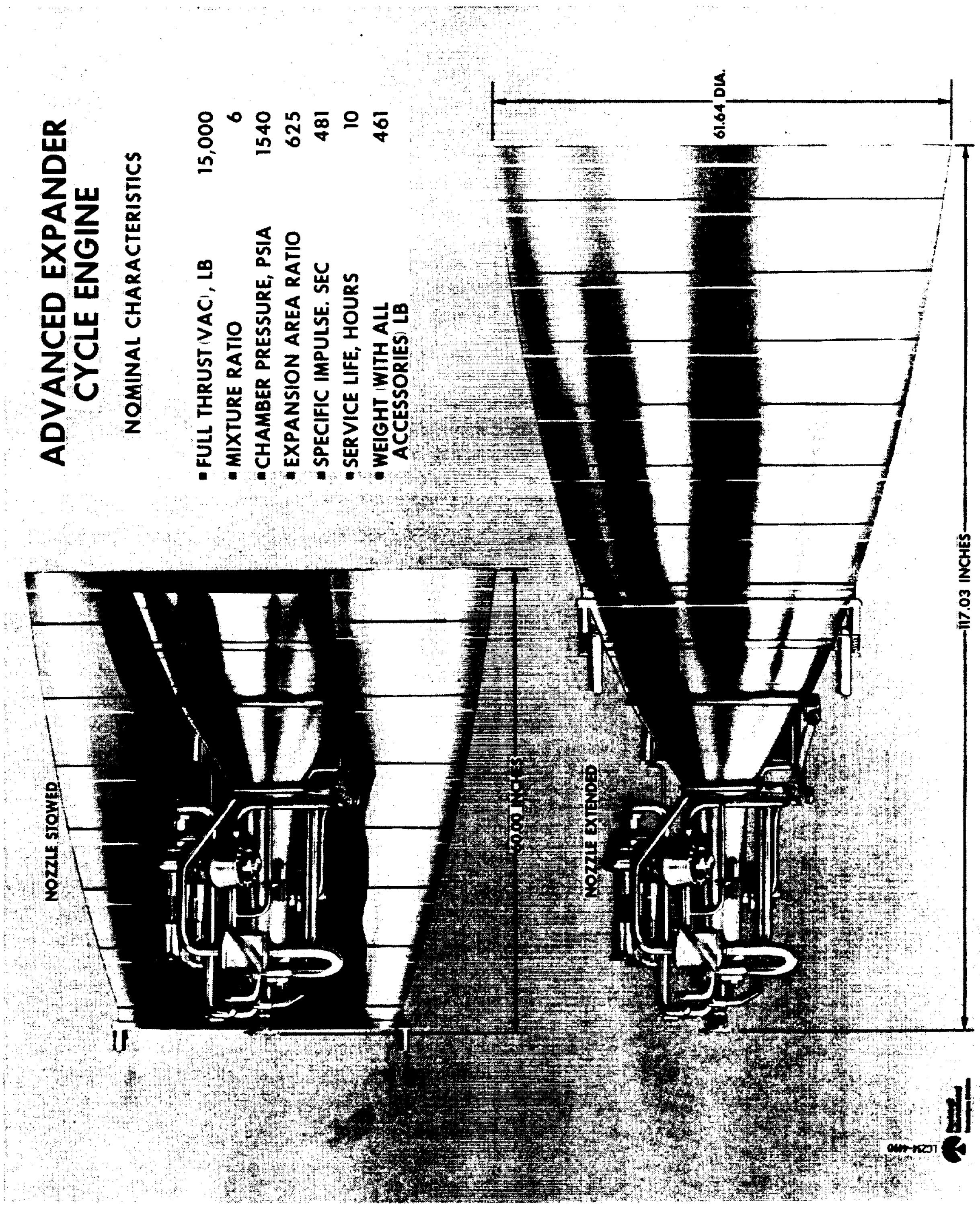

ADVANCED EXPANDER
CYCLE ENGINE
NOMINAL CHARACTERISTICS
FULL THRUST (VAC), LB 15,000
MIXTURE RATIO 6
CHAMBER PRESSURE, PSIA 1540
EXPANSION AREA RATIO 625
SPECIFIC IMPULSE, SEC 481
SERVICE LIFE, HOURS 10
WEIGHT (WITH ALL ACCESSORIES) LB 461
NOZZLE STOWED
60.00 INCHES
NOZZLE EXTENDED
117.03 INCHES
61.64 DIA.

Figure 1

7-19-90

OTV ENGINE SCHEMATIC

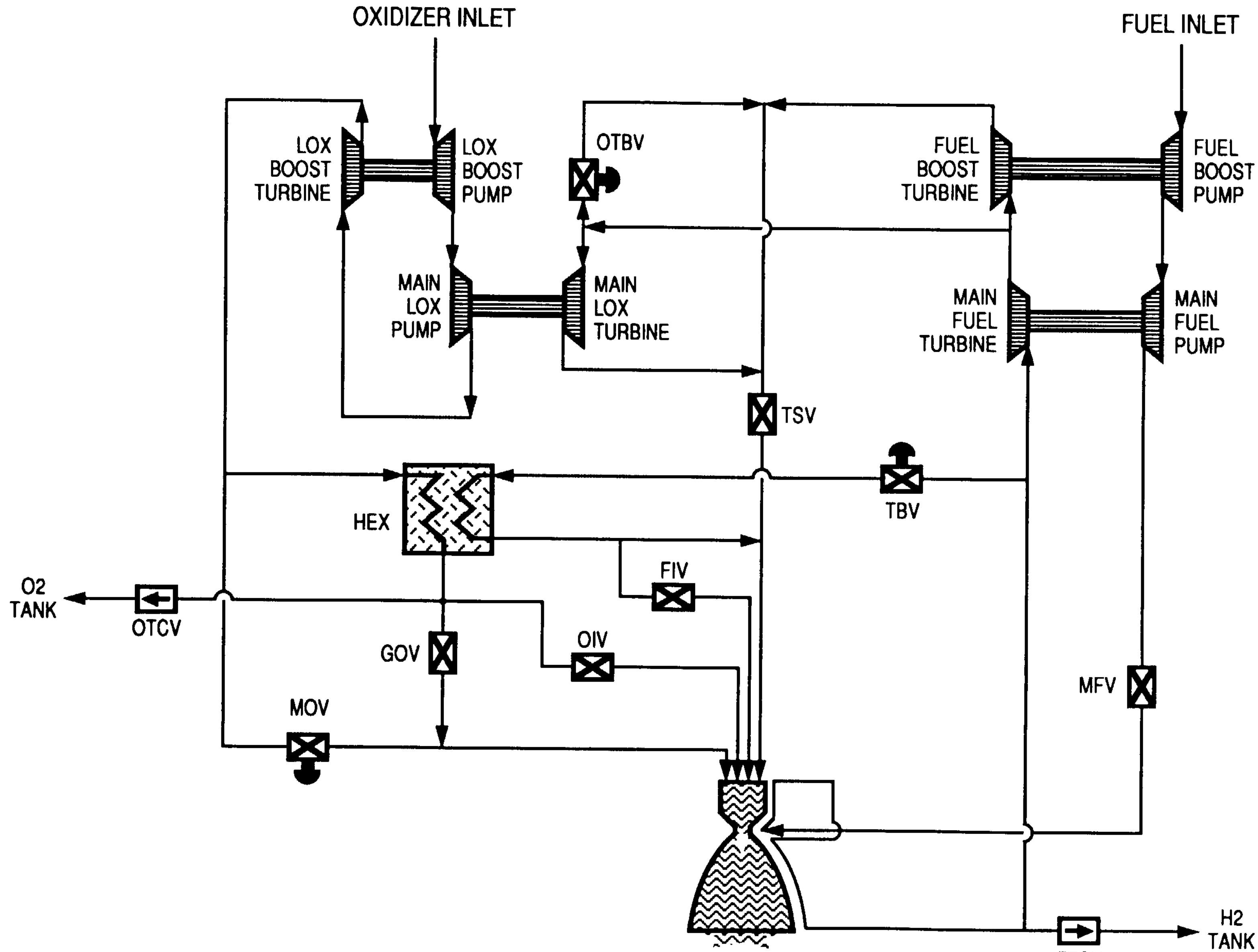


Figure 2

The details of this selection and estimation process are outlined below, beginning with the requirements flowdown process and description of minimal ICHM functions, continuing with a definition and description of the elements and sub-elements of the minimal ICHM system, and concluding with discussions of these elements' technology readiness and estimated development costs.

1.1 Requirements Flowdown

Given an input of general, programmatic requirements, the functions of any particular sub-system can be derived through a flowdown process. The requirements driving ICHM elements came from surveys of NASA Lewis representatives (program monitors) connected with the Earth to Orbit and OTV programs, examination of relevant NASA-LeRC briefings and previous reports, discussions with Rocketdyne personnel experienced in controls / monitoring and engine systems development , review of previous reports on health monitoring systems (OTV-ICHM, HMRSE, ICS, SAFD, Mass Data Storage, etc.), and discussions with control and monitoring system component vendors.

The inputs for the flowdown analysis of engine requirements were; A) baseline assumptions, B) engine system operability characteristics.

Baseline assumptions:

A1. Operation in space environment
(in particular, the ambient conditions over the range of mission profiles)

A2. Mission characteristics
(in particular, the number of engine starts, the time between starts, and the duration of each engine engagement)

A3. Controlled features of external engine structure
(gimballing of engines by actuation, retractable nozzle, etc.)

A4. Engine cycle and capabilities
(specifically, a continuously throttleable to 20:1, hydrogen–oxygen open expander cycle, using electromechanical actuation (with pneumatic failsafe overrides and having approximately 20 Klbs thrust and Isp of 485 seconds with the extendable nozzle)

A5. Use of redundant/ backup systems
(desired for sensors, valves, actuators, processor, electronics, harnesses, software, etc. where practicable)

A6. Minimal ICHM weight

(flight-weight valves, sensors, electronics, etc.)

A7. Expandable system design

(after the minimal system elements are defined, potential growth modes are to be specified and prioritized.)

In particular the features prioritized during customer discussions (see Appendix 2), with less than a priority value of 10 (on a scale of 1 to 10, where 10 is highest) are:

- Robust engine-out capability (data was uncertain, but treated as "10" and thereby included in the minimal ICHM system, this may be a vehicle function)
- Automated diagnostics to determine ability to complete mission (8)
- Incorporation of advanced monitoring and/or control techniques as they become sufficiently developed and/or available((6)
- Real-time diagnostics and prognostics tied to adaptive controls/ knowledge based systems (6)
- Automated pre-mission checkout, includes inspection (4)
- Extended operation at LOX-rich mixture ratios (3)
- Automated life prediction (2)

All of these ICHM-relevant "inputs" can be consolidated and formulated into general and fundamental, programmatic, "operability" requirements as follows:

Engine System Operability Characteristics

B1. Performance (incorporates A4 and A6)

This represents the need to maintain the specified envelope of thrusts and mixture ratios to a specified accuracy.

B2. Flexibility (incorporates A7)

This translates into a requirement for an engine controller to actively govern engine operations during all mission phases: Automated Start/ Restart in Zero-G (Vehicular Pre-Start Readiness Check, etc.), Tank Head Start/ Idle, Steady State (throttling control, gimballing, etc.), Normal and Fail-safe Shutdown in Zero-G, Post-Mission (automated post-shutdown diagnostics for "engine OK/ not OK"), and Between-Mission (possibly with nozzle retraction).

B3. Maintainability (incorporates A4 and A7)

This is the capability for automated engine condition diagnosis, via a health monitoring system ensuring the space-based engine has a service-free life.

B4. Reliability/ Safety (incorporates A5, A6, and A7)

This requirement is enhanced by health (condition plus safety) monitoring, suitable sensor and electronics redundancies (for single and dual engine reliability), and appropriate engine control (fail operational / failsafe) capabilities.

B5. Reusability (incorporates A1, A2, and A3)

This requires the engine to function properly in a space environment with the given life, start and duration characteristics.

As an initial step, these operability requirements were applied to the most recent baseline engine schematic being used in current power balance runs, yielding an updated engine schematic. This update was annotated to show parametric values for states spanning the operating range of thrust levels and mixture ratios.

1.2 Derivation of ICHM Functions

Each requirement was evaluated for its impact upon the ICHM, and a condensed subset of the requirements emerged which could be mapped to corresponding minimum functions for the ICHM to perform.

Condensed Requirement Set: (Quantification based upon NASA-LeRC CTP-ICHM NASA-Contractor Videoconference Briefing, 1990)

- Nominal Engine Operation Control
- Start and Cutoff Control in a Zero-G Environment
- Throttling Capability - 10:1
- Performance Control within $\pm 1\%$ for Thrust and Mixture Ratio (MR), based on the expected mission profile and current capabilities
- Single Engine Reliability - fail op/fail safe (0.9975)
- Dual Engine Reliability - fail op/fail safe (0.99958)
- Service Free Life - 100 starts, 4 hours of operation

- Space Based Operations - no EVA
- Robust Engine Out Capability.

Each of the OTVE system requirements listed above were evaluated by control system and engine system engineers in order to determine the minimum ICHM functions needed to meet each requirement. The requirements were mapped to the corresponding minimum functions which the ICHM must perform. The results of this evaluation are shown in Figure 3. The dots represent which OTVE system requirements are fulfilled by the function. The resulting ICHM minimum functions were grouped by engine operation phase. In addition, Figure 3 shows the Safety Monitoring Functions which are active during all engine phases and the Engine Diagnostics Functions, which are active between missions. Figure 4 depicts element definition from requirements.

Requirements and Corresponding Functions

	ICHM Minimum Functions / ICHM Requirements	Nominal Engine Operations	Start and Cutoff in Zero-G	Throttling	Performance Requirements	Single Engine Reliability	Dual Engine Reliability	Service Free Life	Space Based	Robust Engine Out Capability
Start	Pre-Start Checkout	●							●	
	Engine Conditioning	●								
	Start Ready Verification		●							
	Tank Head Sequence		●							
	Tank Head OK Verification		●							
	Pump Idle Ready Verification		●							
	Pump Idle Sequence		●							
	Pump Idle OK Verification		●							
	Main Stage Ready Verification		●							
	Main Stage Transition		●							
	Main Stage OK Verification		●							
	Start Transient Abort Sequences		●							
Mainstage	Closed Loop, Proportional Thrust Control		●	●	●					
	Closed Loop, Proportional MR Control		●	●	●					
	Multi-Variable (Coupled) Thrust/MR Control		●	●	●					
	Propulsion Level Thrust Vector Control					●				●
	Management of Coolant Resources				●	●	●			
Shutdown	Mainstage Cutoff Sequence		●							
	Engine Safing	●								
	Passive Cutoff System	●								
	Retractable Nozzle Control	●								
Safety Monitoring	Redline Monitoring					●	●			●
	Failure Detection/Accom Algo/Model					●	●			●
Condition Monitoring	Maintenance Algorithms					●			●	
	Control System Fault Detection					●		●		
	Post Hot-Fire OK Verification					●		●	●	

FIGURE 3

ICHM Elements—From Requirements Flowdown

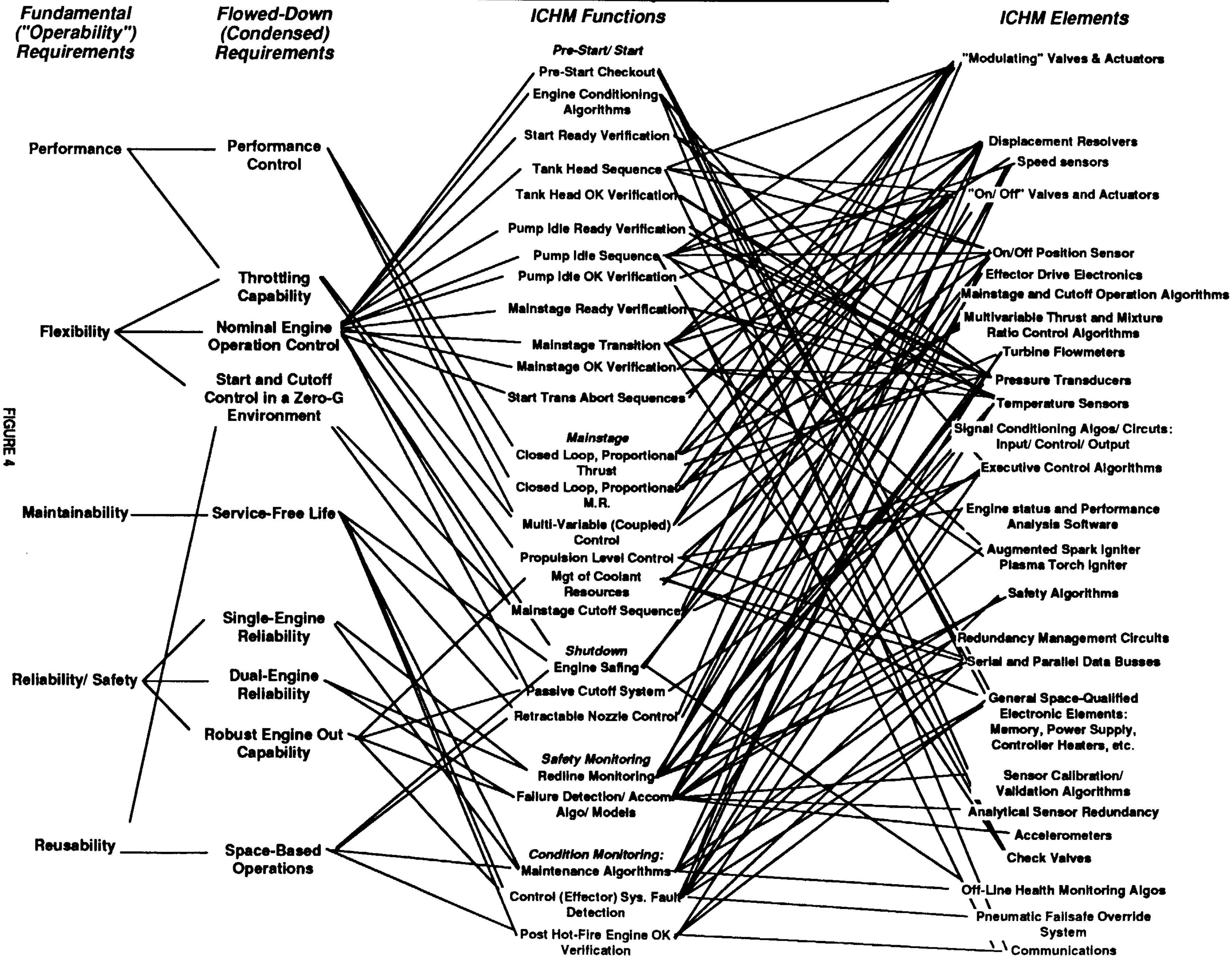


FIGURE 4

2.0 ICHM ELEMENT DESCRIPTIONS AND LISTS

In this section, the element selections and associated rationales are presented along with summary lists and descriptions of the sensor, actuator, electronic hardware and software elements and sub-elements. In selecting many of the system sub-elements, several valid alternative technical approaches, representing different levels of technology readiness and desirable performance/physical characteristics, were considered. Where applicable, these alternatives are discussed as well as the assumptions and criteria underlying the baseline element selections.

The ICHM system elements can be categorized into four distinct areas, see Figure 5:

I. Sensors
II. Effectors (valves, actuators, igniters)
III. Electronics (controller, data storage, harnesses)
IV. Algorithms and software (control algorithms, health monitoring software)

2.1 Sensors

After the functions were determined, a list of sensors needed to perform the functions was generated. The measurements were correlated to the function(s) they serve, as shown in Figure 6.

Experienced engine systems personnel participated in the effort to minimize the number of recommended measurements. The eliminated measurements, the rationale for elimination and a brief explanation is given in Table 1. Figure 6 does not include the eliminated sensors.

There are seven basic types of measurements used in the minimum ICHM system:

1. Static pressure
2. Static temperature
3. Flow
4. Speed
5. Displacement (Continuous)
6. Position (On/Off)
7. Acceleration

The operating ranges for each sensor type in the measurements matrix were obtained through engine balance data. This data was examined for three "operating points", shown in Table 2.

OTVE ICHM ELEMENT ARCHITECTURE

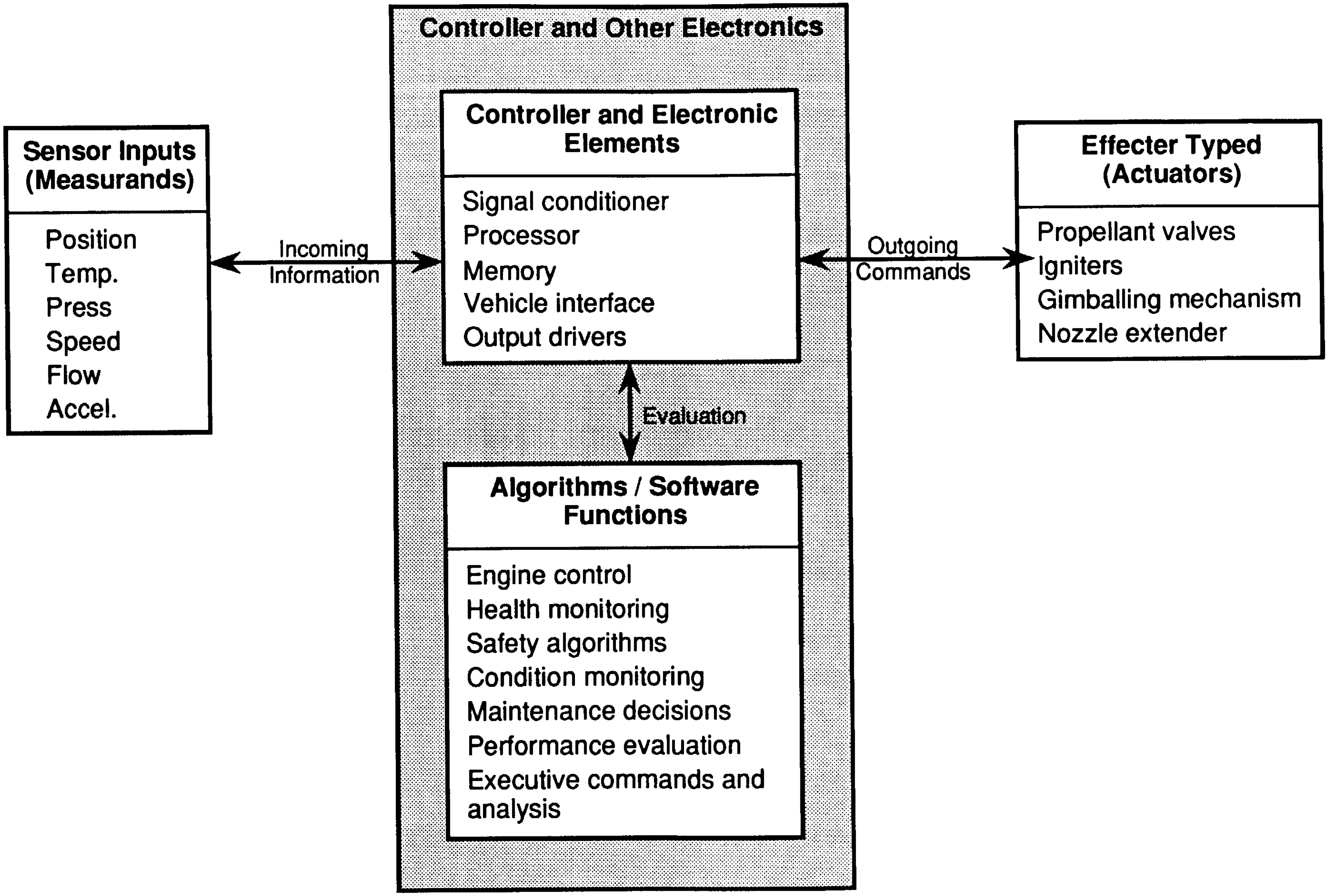


Figure 5

91-MA-113-008- 2

ICHM MEASUREMENT LIST (1 of 3)

	ICHM FUNCTIONS	PRE-START CHECKOUT	ENGINE CONDITIONING	START READY VERIFICATION	TANK HEAD SEQUENCE	TANK HEAD OK VERIFICATION	PUMP IDLE READY VERIFICATION	PUMP IDLE SEQUENCE	PUMP IDLE OK VERIFICATION	MAIN STAGE READY VERIFICATION	MAIN STAGE TRANSITION	MAIN STAGE OK VERIFICATION	START TRANS ABORT SEQUENCES	CLOSED LOOP, PROP THRUST	CLOSED LOOP, PROP MR	MULTI-VARIABLE (COUPLED) CONTROL	PROPULSION LEVEL CONTROL	MANAGEMENT OF CLNT RESOURCES	MAINSTAGE CUTOFF SEQUENCE	ENGINE SAFING	PASSIVE CUTOFF SYSTEM	RETRACTABLE NOZZLE CONTROL	REDLINE MONITORING	FAILURE DETECTION ALGORITHMS	MAINTENANCE ALGORITHMS	CONTROL SYSTEM FAULT DETECTION	POST HOT-FIRE ENGINE OK VERIF.
	PRESSURE																										
P1	Controller internal Pr	●																								●	
P2	HPOP I. S. cavity Pr																●						●	●			
P3	HPFP discharge Pr																							●	●		
P4	HPFP inlet Pr						●		●	●		●												●	●		
P5	HPFT discharge Pr																								●		
P6	HPFT inlet Pr																								●		
P7	HPOP discharge Pr																							●	●		
P8	LPOP inlet Pr	●																							●		
P9	HPOT discharge Pr																								●		
P10	HPOTP interm. seal purge Pr			●													●						●				
P11	LPFP inlet Pr	●																							●		
P12	LPOT discharge Pr																								●		
P13	MCC Pc					●			●			●		●		●	●						●	●	●		
P14	Pneumatic C/O syst. Pr	●		●																					●		
P15	Tank Pr								●															●	●		
	POSITION																										
L1	GOV position				●			●					●			●			●	●	●					●	
L2	MOV position				●			●			●		●		●	●			●	●	●					●	
L3	MFV position	●	●		●			●					●			●			●	●	●					●	
L4	FTBV position				●			●			●		●	●		●	●		●	●						●	
L5	TSV position	●	●		●			●					●						●	●						●	
L6	Nozzle extender	●		●																		●				●	
L7	OTBV position							●			●		●		●	●			●	●						●	
L8	IGOV position												●						●	●							
L9	IGFV position												●						●	●							

FIGURE 6, ICHM MEASUREMENT LIST (1 of 3)

ICHM MEASUREMENT LIST (2 of 3)

ICHM FUNCTIONS	TEMPERATURE	PRE-START CHECKOUT	ENGINE CONDITIONING	START READY VERIFICATION	TANK HEAD SEQUENCE	TANK HEAD OK VERIFICATION	PUMP IDLE READY VERIFICATION	PUMP IDLE SEQUENCE	PUMP IDLE OK VERIFICATION	MAIN STAGE READY VERIFICATION	MAIN STAGE TRANSITION	MAIN STAGE OK VERIFICATION	START TRANS ABORT SEQUENCES	CLOSED LOOP, PROP THRUST	CLOSED LOOP, PROP MR	MULTI-VARIABLE (COUPLED) CONTROL	PROPULSION LEVEL CONTROL	MANAGEMENT OF CLNT RESOURCES	MAINSTAGE CUTOFF SEQUENCE	ENGINE SAFING	PASSIVE CUTOFF SYSTEM	RETRACTABLE NOZZLE CONTROL	REDLINE MONITORING	FAILURE DETECTION ALGORITHMS	MAINTENANCE ALGORITHMS	CONTROL SYSTEM FAULT DETECTION	POST HOT-FIRE ENGINE OK VERIF.
T1	GOV skin tmp																									●	
T2	HEX fuel discharge tmp																●						●				
T3	HEX oxidizer discharge tmp		●														●						●				
T4	HPFP discharge tmp																							●	●		
T5	HPFP inlet tmp		●				●	●		●		●												●	●		
T6	HPFT discharge tmp																								●		●
T7	Nozzle coolant exit tmp					●				●		●					●	●					●	●			
T8	HPOP inlet tmp		●				●	●		●		●												●	●		
T9	HPOT discharge tmp																								●		●
T10	LPFP inlet tmp																								●		
T11	LPOP inlet tmp																								●		
T12	LPOT discharge tmp																								●		
T13	MFV skin tmp		●																							●	
T14	MOV skin tmp		●																							●	
T15	Controller internal tmp	●																									
T16	MCC coolant DS tmp																										

FIGURE 6, ICHM MEASUREMENT LIST (2 of 3) 7-26-91

ICHM MEASUREMENT LIST (3 of 3)

	ICHM FUNCTIONS	PRE-START CHECKOUT	ENGINE CONDITIONING	START READY VERIFICATION	TANK HEAD SEQUENCE	TANK HEAD OK VERIFICATION	PUMP IDLE READY VERIFICATION	PUMP IDLE SEQUENCE	PUMP IDLE OK VERIFICATION	MAIN STAGE READY VERIFICATION	MAIN STAGE TRANSITION	MAIN STAGE OK VERIFICATION	START TRANS ABORT SEQUENCES	CLOSED LOOP, PROP THRUST	CLOSED LOOP, PROP MR	MULTI-VARIABLE (COUPLED) CONTROL	PROPULSION LEVEL CONTROL	MANAGEMENT OF COOLANT RESOURCES	MAINSTAGE CUTOFF SEQUENCE	ENGINE SAFING	PASSIVE CUTOFF SYSTEM	RETRACTABLE NOZZLE CONTROL	REDLINE MONITORING	FAILURE DETECTION ALGORITHMS	MAINTENANCE ALGORITHMS	CONTROL SYSTEM FAULT DETECTION	POST HOT-FIRE ENGINE OK VERIF.
	FLOW																										
M1	fuel flowrate														●	●	●							●	●		
M2	oxidizer flowrate														●	●	●							●	●		
	SPEED																										
S1	HPFTP speed								●			●											●	●	●		
S2	HPOTP speed								●			●											●	●	●		
S3	LPFTP speed								●			●													●		
S4	LPOTP speed								●			●													●		
	VIBRATION																										
V1	HPFTP vibration																●							●			●
V2	HPOTP vibration																●							●			●
V3	LPFTP vibration																●							●			●
V4	LPOTP vibration																●							●			●
	ELECTRICAL																										
E1	spark igniter output current	●		●	●												●									●	
E2	spark igniter output voltage	●		●	●												●									●	
E3	valve driver output current	●		●									●				●		●	●						●	
E4	valve driver output voltage	●		●									●				●		●	●						●	

FIGURE 6, ICHM MEASUREMENT LIST (3 of 3)

Measurement Location and Type	Rationale	Explanation for Elimination of Measurement
Hydrostatic Bearing Inlet Pressure (8)	Redundant	Would duplicate information given by pump discharge pressure
Fuel Injector Pressure	Ineffective	This ΔP information would not provide conclusive condition assessment of the injector, due to the cancelling effects of erosion and corrosion
Combustion chamber inlet (after GOV) Pressure	Redundant	Would duplicate information easily calculated from the LOX main turbine outlet pressure and the GOV resistance
Oxidizer CC Injection Pressure	Redundant	Would duplicate information easily calculated from the LOX boost turbine outlet pressure and the MOV resistance
Main LOX Pump Discharge Pressure	Redundant	Would duplicate information given by main LOX turbine inlet pressure
Boost LOX Turbine Inlet Pressure	Redundant	Would duplicate information given by main LOX pump discharge pressure
Main LOX Turbine Inlet Pressure	Redundant	Would duplicate information given by main fuel turbine discharge pressure
Boost LOX Pump Discharge Pressure	Redundant	Would duplicate information given by LOX tank pressure, which is the more useful
Main LOX Turbine Seal Drain Pressure	Redundant	Would duplicate information given by the seal inlet and purge pressures, due to the relative incompressibility of LOX
FTBV Skin Temperature	Unnecessary	Since this valve never needs to be fully closed, sealing is not an issue
TSV Skin Temperature	Unnecessary	Specific knowledge regarding leakage in this valve is unnecessary; general information is contained in the pump discharge pressures
Fuel Valve Skin Temperature	Unnecessary	Specific knowledge regarding leakage in this valve is unnecessary, since characterization will be sought during development; sufficient information is contained in the MFV skin temperature
Main Fuel Turbine Temperature	Redundant	Would duplicate information given by the nozzle coolant exit temperature
Main Oxidizer Turbine Temperature	Unnecessary	Would provide (unnecessary) information regarding pump efficiency only; unjustifiable in view of harsh environment
Boost Fuel Turbine Temperature	Unnecessary	Information unnecessary and of limited value
Main Fuel Turbine Flow	Unnecessary	Characterization of injector during design and development will ensure flow stability
Powerhead Acceleration	Unnecessary	An optional feature

Table 1. Measurement List Reduction Rationale

Design Point	Thrust Level	Mixture Ratio
On-design engine	100%, 20K	6:1
Off design (1)	100%, 20K	5:1
Off design (2)	5%, 1K	6:1

TABLE 2, ENGINE BALANCE OPERATING POINTS

These engine balances, shown in Figures 7, 8 and 9, show the flow, pressure and temperature at various engine locations. All of this data, taken together, span the range of operating conditions currently under consideration for the OTVE engine and represents the range of conditions that will be seen by these sensor types. Sensor selections, shown with accompanying rationale in Table 3, were driven by operating condition ranges and needed measurements.

Measurement Type and Sensor Technology	Rationale
Static Pressure: Silicon on Sapphire Pressure Sensor	History of long term stability (0.01%/year). Withstands continuous exposure to temperatures of approximately 750°F.
Static Temperature: RTD Temperature Sensor	Proven technology, used on the SSME with a high degree of accuracy and stability.
Flow: Turbine Sensor	Proven technology, used for SSME fuel with a high degree of accuracy.
Speed: Variable Reluctance	Proven technology, used on the SSME.
Continuous Displacement: Resolver	Selected for degree of accuracy needed for deep throttling. Use of this sensor will require some testing in the development of the system.
On/ Off Position: Eddy Current	Compact size, used to detect position for fully open or closed valve. Proven in similar applications on the SSME Technology Test Bed program.
Acceleration Piezo Electric	Proven technology, used on the SSME.

TABLE 3, SENSOR SELECTIONS

7-19-90

OTV ENGINE BALANCE: ON-DESIGN VALUES

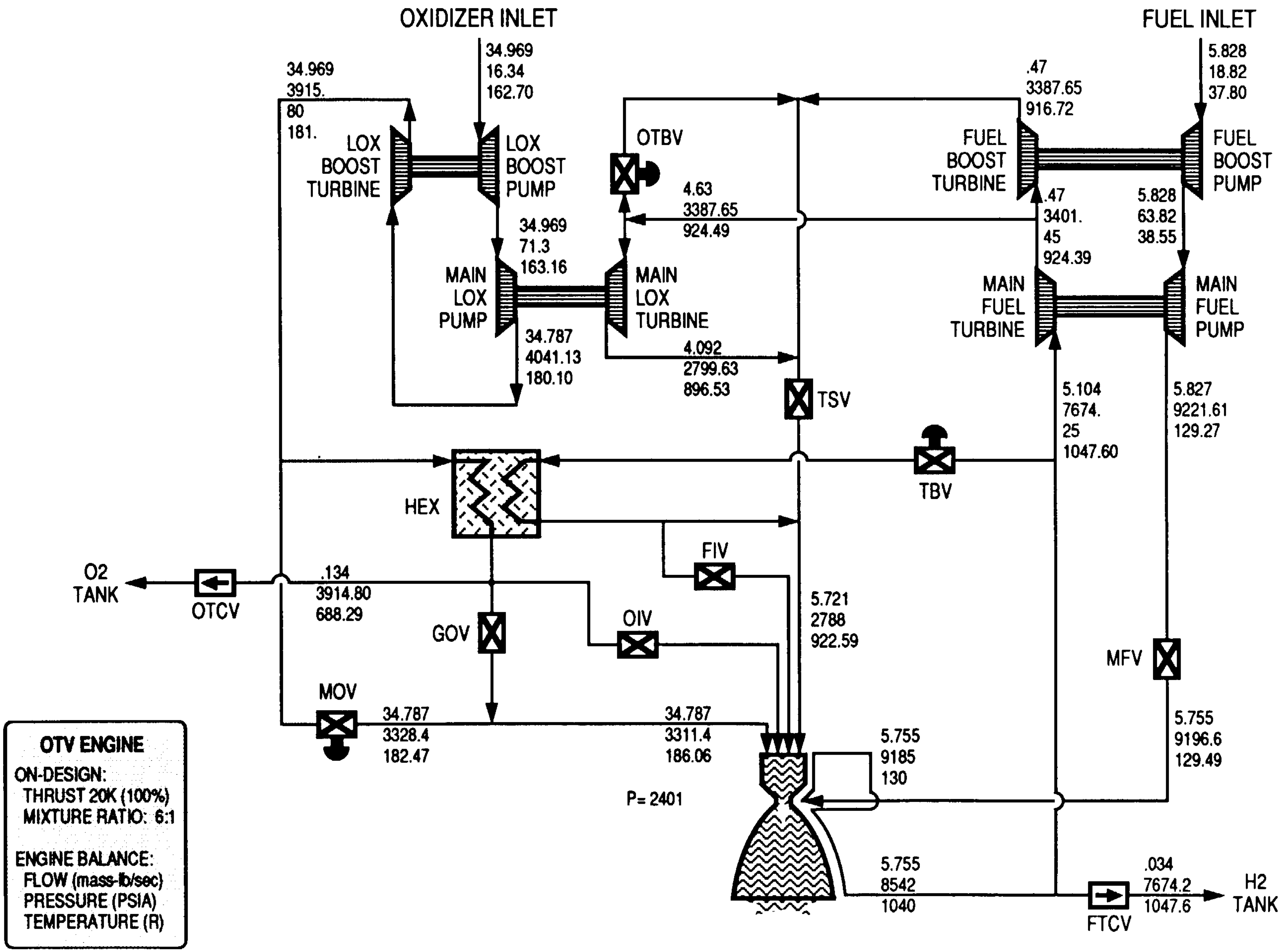


Figure 7

7-19-90

OTV ENGINE BALANCE: OFF-DESIGN VALUES (1)

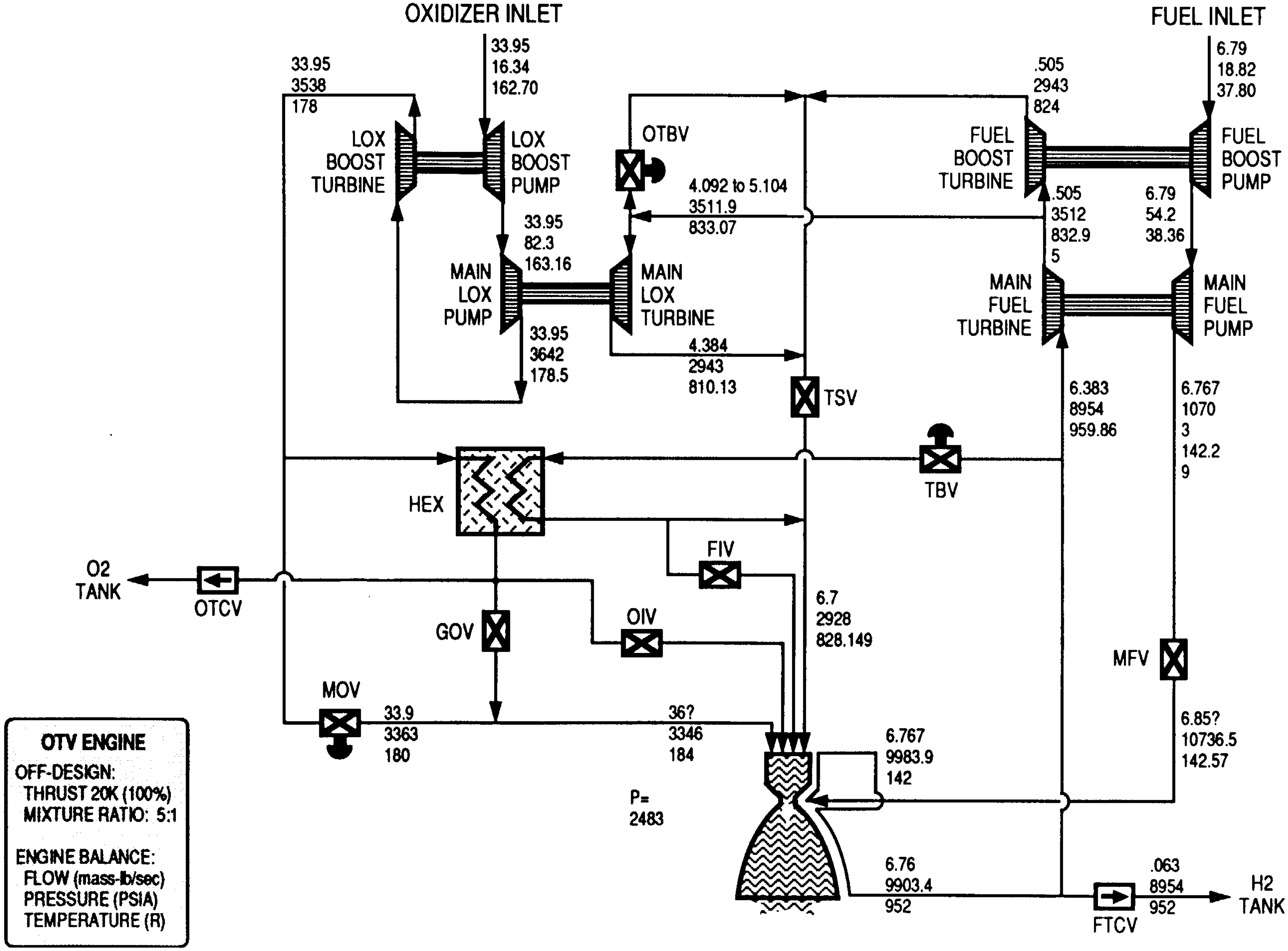


Figure 8

7-19-90

OTV ENGINE BALANCE: OFF-DESIGN VALUES (2)

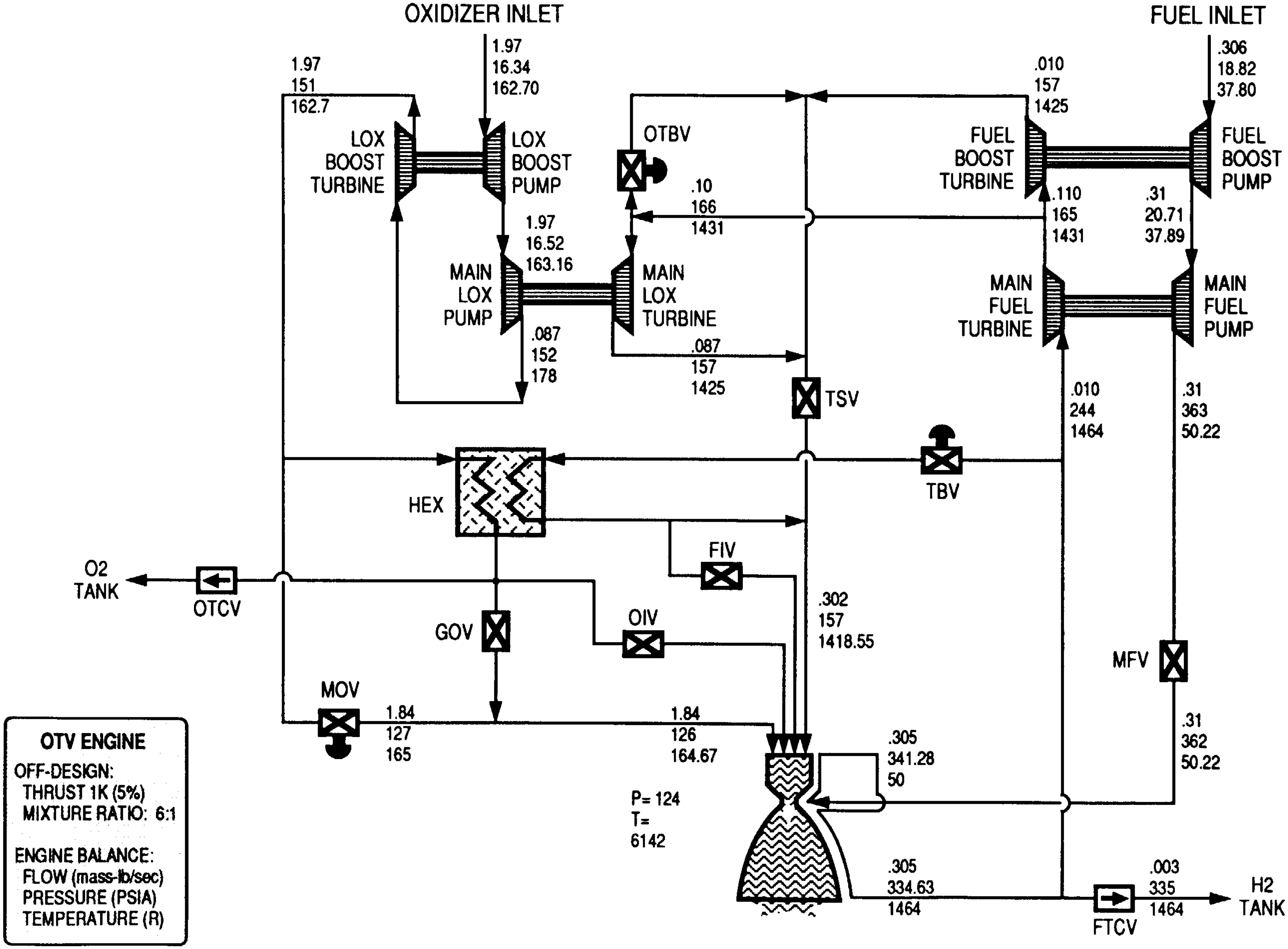


Figure 9

Table 4 shows the selected sensors, the operating ranges, and the several optional sensors. The locations of the sensors on the engine are shown in Figure 10.

2.2 Effectors

The basis for the effector element selection compares available or emerging designs and the requirements of a particular application. Rocketdyne's ongoing development efforts are included in the valve and actuator technologies. A particular goal is a reliable, accurate, easily maintainable electric actuated propellant valve capable of deep throttling. Commencing with the Advanced Space Engine (ASE), an IR&D task was started in 1982 to evaluate and develop electric actuated main propellant valves for orbital transfer vehicles (OTV). This work resulted in design and characterization of a prototype main oxidizer valve for the 15K thrust RS-44 expander cycle engine. An advanced propellant valve based on the prototype main oxidizer valve design is recommended for the OTV engine.

It is assumed that the following elements are supplied by the vehicle contractor:

I. Propellant tank pressure regulation components (regulator/ relief valves)
Fuel Tank Pressurization System using autogenous gas from engine
Oxidizer Tank Pressurization System- using autogenous gas from engine

II. Inlet Propellant Valves
Fuel Inlet Valve
Oxidizer Inlet Valve

(The propellant tank isolation check valves are considered as part of the engine system as they are contained within the engine to tank pressurization lines. In order to provide a more complete design description, system requirements will need to be established for these check valves as well as the nozzle extender and thrust vector actuators).

The ICHM has the following propellant valves and components for engine control (component types and positions are identified in Table 5):

1. Main fuel valve (MFV)
2. Main oxidizer valve (MOV)

3. Turbine bypass valve (TBV)
4. Oxidizer turbine bypass valve (OTBV)
5. Turbine shutoff valve (TSV)
6. Gaseous oxidizer valve (GOV)
7. Oxidizer igniter valve (OIV)
8. Fuel igniter valve (FIV)
9. Oxidizer tank check valve (OTCV)
10. Fuel tank check valve (FTCV)
11. Pneumatic fail-safe system (PFS)
12. Nozzle extender actuator (NEA)
13. Thrust vector actuator (TVA)
14. Augmented spark igniter (ASI)

Sensor Technology Selections

MEASURE-MENT TYPE	STATIC PRESSURE	STATIC TEMPERATURE	FLOW	SPEED	DISPLACEMENT (continuous)	POSITION (on/off)	ACCELER-ATION
RECOMMENDED TECHNOLOGY	Silicon on Saphire	Resistive Temperature Device	Turbine	Variable Reluctance	Resolver	Eddy Current	Piezoelectric
OPERATING RANGE	0/9000 PSI	LH2/+1400 °F	0/40 Lbm/sec	0/200,000 RPM	0/90 degrees	n/a	0/100,000 g
MEASUREMENT UNCERTAINTY	0.5% full scale	0.1% full scale	1.0% full scale	0.5% full scale	0.25% full scale	TBD	TBD
NOMINAL OUTPUT	0/50 mV d.c.	Bridge-dependent	Computed quantity	TBD V a.c.	TBD	5 V d.c. max	100,000 pC
OPERATING TEMPERATURE	0/1000 to 1500 R	20/1500 R	30/1500 R	0/1000 to 1500 R	30/1500 R	30/1500 R	20/1500 R
OPERATING PRESSURE	25/4000 PSIA typical	10/4000 PSIA	100/11,000 PSIA	10/10,000 PSIA	100/11,000 PSIA	100/4000 PSIA	100/10,000 PSIA
ALTERNATE TECHNOLOGY #1	Piezoresistive		Ultrasonic	Torquemeter	L.V.D.T. *	Limit Switches	
ALTERNATE TECHNOLOGY #2						Proximity Switches	
COMMENTS AND LEGEND	Extremes range from 0 to11,000 PSIA	Element is 50/5000 ohm	Need pressure and tempera-ture to compute	May combine with torque measurement	* Linear Variable Displace-ment Transformer		pC = pico-Coulombs, R = Rankine

Table 4

OTV ENGINE WITH SENSOR LOCATIONS

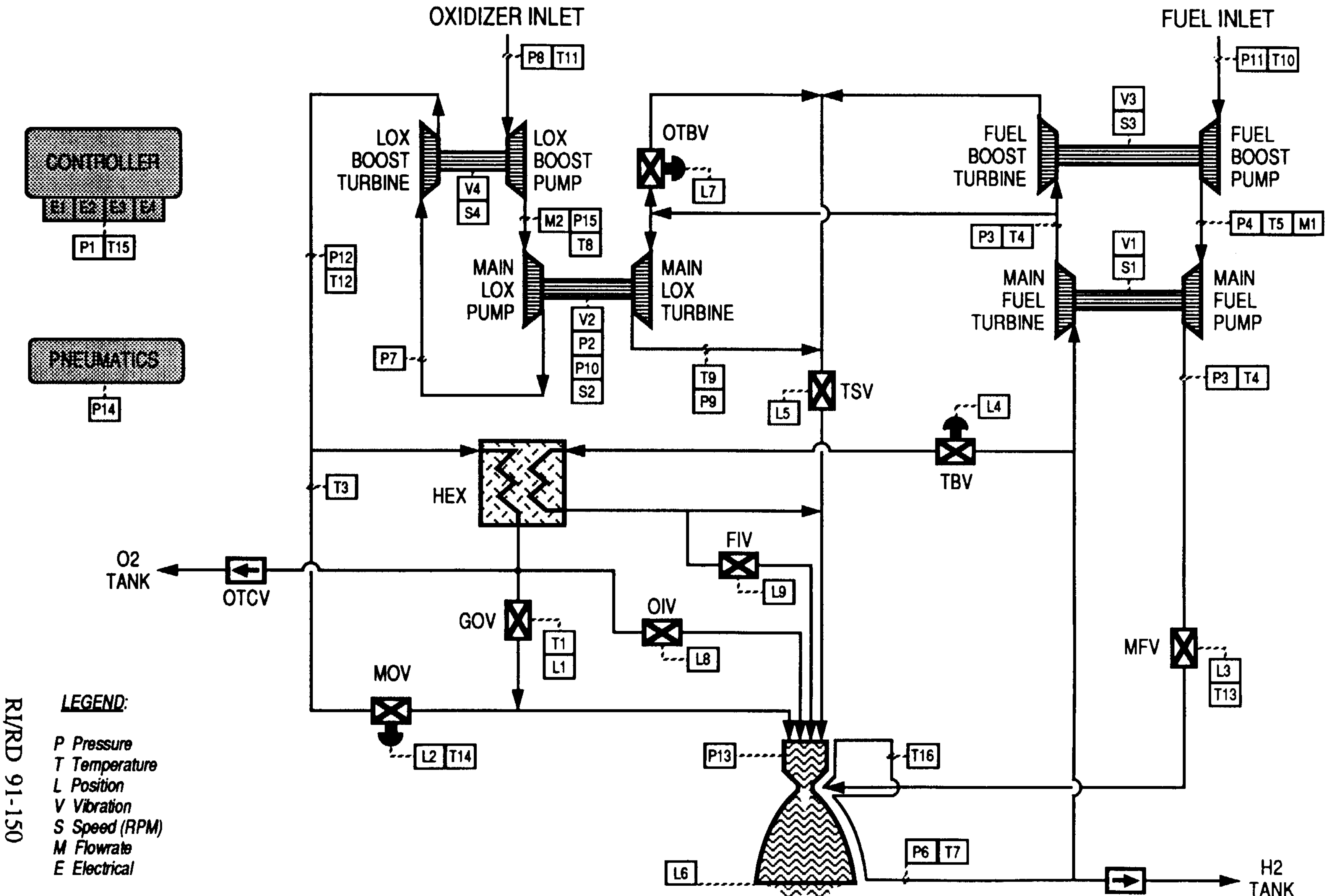


Figure 10

NO.	FUNCTION	TYPE	FLUID	ENGINE MODE	VALVE POSITION
1	Main Fuel Valve (MFV)	Venturi Ball Valve Electric Actuator On-Off Control	LH2	MS PI THI S	OPEN OPEN OPEN OPEN
2	Main Oxidizer Valve (MOV)	Sector Ball Valve Electric Actuator Modulating Control	LOX	MS PI THI S	THROTTLED THROTTLED CLOSED CLOSED
3	Turbine Bypass Valve (TBV)	Sector Ball Valve Electric Actuator Modulating Control	GH2	MS PI THI S	THROTTLED OPEN OPEN OPEN
4	Oxidizer Turbine Bypass Valve (OTBV)	Sector Ball Valve Electric Actuator Modulating Control	GH2	MS PI THI S	THROTTLED THROTTLED THROTTLED OPEN
5	Turbine Shutoff Valve (TSV)	Venturi Ball Valve Electric Actuator On-Off Control	GH2	MS PI THI S	OPEN OPEN CLOSED CLOSED
6	Gaseous Oxidizer Valve (GOV)	Poppet Valve Solenoid-operated On-Off Control	GOX	MS PI THI S	CLOSED CLOSED OPEN CLOSED
7	Oxidizer Igniter Valve (OIV)	Poppet Valve Solenoid-operated On-Off Control	GOX	MS PI THI S	OPEN OPEN OPEN
8	Fuel Igniter Valve (FIV)	Poppet Valve Solenoid-operated On-Off Control	GH2	MS PI THI S	OPEN OPEN OPEN OPEN
9	Oxid. Tank Check Valve (OTCV)	Check Valve	GOX		
10	Fuel Tank Check Valve (FTCV)	Check Valve	GH2		
11	Pneumatic Failsafe System (PFS)	Solenoid-operated			
12	Nozzle Extender Actuator (NEA)	Electric Actuator On-Off Control			
13	Thrust Vector Actuator (TVA)	Electric Actuator 6–15 deg Modulating Control in both X- and Y- axes			
14	Augmented Spark Igniter (ASI)	Spark Igniter			

ENGINE MODE LEGEND: (20K Thrust) THI = Tank Head Idle S=Start
MS = Main Stage PI = Pumped-Idle

Table 5. Effectors

A brief discussion of the control valve functions during engine start, tank head idle, pumped idle, and main stage operation is presented on the following pages.

Main Fuel Valve (MFV)

The MFV is an electric actuated on/off cryogenic valve which opens fully to permit fuel flow at engine start and remains open throughout all of the engine operational modes. Minimum pressure drop in the fuel circuit is required along with capability for tight shutoff.

Main Oxidizer Valve (MOV)

The MOV is a fully modulating cryogenic valve responsible for mixture ratio control. During start and tank head idle the valve is fully closed forcing LOX through the GOX heat exchanger. At pumped idle the valve is ramped, open loop, to an intermediate position providing limited oxidizer flow to the engine. At main stage the valve opens more fully and is under closed loop control on mixture ratio. This valve must be capable of tight shutoff.

Turbine Bypass Valve (TBV)

The TBV is a modulating valve with no tight shutoff requirement which controls engine thrust by throttling fuel flow to the turbines. During start and tank head idle this valve is full open allowing fuel from the nozzle to bypass the turbines and flow through the GOX heat exchanger to provide gaseous oxygen flow to the igniter and combustor. During pumped idle the TBV is maintained full open as the turbine shutoff valve (TSV) is opened which results in some fuel flow to the turbines. At mainstage the TBV is in its most throttled position modulating under closed loop control on thrust.

Oxidizer Turbine Bypass Valve (OTBV)

The OTBV is similar to the TBV in that it is also a modulating valve with no tight shutoff requirements. Its primary purpose is to balance the oxidizer and fuel pump turbines. During start and tank head idle the valve is at full open or an intermediate position but does not control any flow as the TSV is closed. During pumped idle (with the TSV open) the OTBV is ramped, open loop, to an intermediate position which forces some fuel through the oxidizer main pump turbine. At mainstage the OTBV is in its most throttled position under closed loop control on pump turbine balance.

Turbine Shutoff Valve (TSV)

The TSV is an on/off valve which is closed during start and tank head idle mode with minimal turbine gas flow such that the turbines do not spin. The valve is ramped to full open during pumped idle and remains open at main stage. Like the MFV, a minimum pressure drop is required.

Gaseous Oxidizer Valve (GOV)

The GOV is a two way (on/off) direct or pilot operated solenoid valve, open only during tank head idle operation providing gaseous oxygen flow to the combustor. During the transition to pumped idle the valve is closed.

Igniter Valves (OIV, FIV)

The igniter valves are two way (on/off) solenoid valves which provide gaseous oxidizer and fuel to the igniter throughout all engine operational modes.

Propellant Tank Check Valves (FTCV, OTCV)

The FTCV and OTCV prevent backflow from the cryogenic propellant tanks to the turbines when the engine is inactive. The check valves also serve to isolate propellant between each engine.

Nozzle Extender Actuator (NEA)

The NEA is a linear electrically actuated system which extends a radiation cooled nozzle. Following engine shutdown, the NEA retracts the nozzle back to the stowed position when required.

Thrust Vector Actuator (TVA)

The TVA consists of two linear electric actuators which provide gimballing control. The TVA will provide 6 to 15 degrees modulating control in both x and y axes.

Augmented Spark Igniter (ASI)

Two Augmented Spark Igniters (ASI) will be used to ensure reliability. The components for the igniter include:

1. Electronic ignition exciter (2)
2. High-voltage cable (2)
3. Spark igniter plug (2)
4. Ignitor injector/precombustor

All of the components are separable. Spark igniters and the igniter injector are installed using threaded joints. Electronic components are dual redundant. Failure of any single electrical component will not cause ignition failure. Ignition is accomplished by activating the spark system and introducing propellants into the igniter. These propellants are injected in a pattern that provides cold fuel surrounding the oxidizer. This pattern ensures cooling so an additional supplemental cooling system is not required. The ignition system is reusable and restarts without component replacement or servicing.

2.2.1. Effector Design Description

Three types of propellant control valves are proposed for the OTV engine: 1) sector ball valve, 2) venturi ball valve and 3) solenoid operated poppet valves. The sector ball valve will be used for low torque applications. For low pressure drop the venturi ball valve will be used. Low flow ignition and control applications will employ either direct or pilot operated solenoid valves.

Electric Actuated Cryogenic Propellant Control Valves.

The electric actuated MOV consists of a sector ball gate to throttle flow that is supported on integral shafts by a pair of ball bearings, and positioned by an electromechanical actuator with closed loop position feedback from a resolver off the ball shaft. The gate configuration is basically one-half of a spherical shell. Sealing is provided by shaft seals and ball seals of DuPont Vespel. Modular construction permits easy disassembly of the actuator, valve module and seat package from a single valve housing flange. The valve housing can therefore remain attached to the propellant ducts.

A key feature of the Rocketdyne sector valve is the continuous-contact seat seal design. This design is basically similar to the very successful SSME shaft seal subsequently used in the ASE and RS-44 integrated component evaluator (ICE) propellant valves. These designs maintain micro inch level of leakage gap under extremely high bearing loads which is achieved through the unique characteristics of DuPont Vespel SP-211, a combination of polyimide, graphite, and Teflon. The material has demonstrated compatibility with LOX and LH2 over the full range of expected operating conditions. Leakage can be held to less than 10 scim helium, however, higher limits are recommended because system allowances are considerably greater and lower costs result. All external valve leakage can be collected by use of redundant shaft seals and two static flange seals with the intermediate cavities connected to a single housing port for safe venting overboard. This feature permits potential "growth" instrumentation for health monitoring of each valve for external leakage before, during and after each engine firing.

The seat seal package is a modular assembly comprised of a retainer, snap ring, wave springs, loader, and seal. The wave springs provide load to seal at low pressure and also overcome friction forces at cryogenic temperature. All seal design parameters are anchored by test data and defined by computer analysis which permits definition of an optimal design. Equations for seal reaction forces consider thermal contraction, radial seal clearance or interference, pressure differential, loader force, friction and seal material elastic parameters.

Coupling the valve shaft to the actuator is a metal bellows which provides for thermally induced axial motion, is radially stiff, and has no free play. The valve and actuation system is designed to maintain backlash and elastic windup to less than 0.3 degree under maximum load. Response will be less than 1.0 second full travel under maximum load with capability of less than 0.2 second at reduced or aiding loads to permit fast shutdown as required.

The MFV requires a larger flow area than the MOV due to lower pressure drop requirements. A full ball with venturi inlet and outlet flow sections to reduce delta P will be used with the MFV to permit a common valve size with the MOV. Thus the MFV will be identical with the MOV except for the noted variations in closure and flow geometry to provide low pressure drop with nearly common cryogenic propellant valves.

Turbine Gas Valve Design

Turbine gas valves (OTBV, TBV, TSV) are patterned after the MOV but with several variations. Valve body, gate and bearing materials must withstand temperatures to 950 degrees F and pressures to 7674 psia. Although stringent leakage requirements are not required for the seat seal, the shaft seal may see high temperature. Consequently, two paths will be followed to address function of the shaft seal:

1) A carbon/graphite seal will be designed for operation at 950 degrees F, but with the actuator both insulated and thermally isolated from the valve.

2) As backup, polyimide shaft seals will be thermally isolated from the valve with the actuator to prevent seal temperatures exceeding 350 degrees F.

The TSV will have the same full ball venturi flow geometry as the MFV to provide low pressure drop. Additionally the TSV has a requirement to shut-off sufficient turbine gas flow such that the turbines do not spin during tank head idle. Two alternative seat seal designs considered are: 1) an all metal dry film lubricated seat seal as used on the RS-44 TBV and OTBV, and 2) a carbon/graphite design mated with a molybdenum seat tube insert which provides a very close match in thermal expansion with the carbon seal material. Fortunately, this seal needs to operate only at relatively low pressure differential with liberal leakage allowance. Primary parameters to be considered in design are therefore long life and reliability.

Solenoid Operated Valves

The GOV, IGOV and IGFV are two-way solenoid operated valves providing on/off control of GOX and GH2 propellants at low flow rates. Key features are rugged simplicity providing high reliability and low cost. Dual coils can be provided for electrical redundancy as required.

Check Valves

Propellant tank isolation between the OTV engines will be provided by the OTCV and FTCV. These are poppet-type check valves which can be used in series for redundancy as required.

Pneumatic Fail-safe System Components

The pneumatic fail-safe system consists of a regulated pneumatic supply, pneumatic control assembly (PCA) and fail-safe actuators mounted to the necessary engine control valves needed to effect a safe engine shutdown. All control components will have redundant electrical actuator systems such that upon any electrical failure the secondary system can provide fail-operation of the OTV engine. Upon failure of the secondary system, the actuator will lock in position until the pneumatic fail-safe system is energized from the PCA to provide a sequenced valve deactuation that will safely shutdown the engine.

Nozzle Extender and Thrust Vector Actuators

These components are electromechanically actuated with dual electrical redundancy.

2.3 Electronics

The intent of the control system block diagram is to indicate the features which will satisfy the stated requirements and perform the minimum functions necessary for successful OTV operation. A dual channel architecture is the baseline, with additional redundancy possible, each with its own power supply and heater. The architecture will be modular to accommodate additional capability, new technologies, or increased redundancy.

Single channel controller functions are broken down into three main areas; input processing, control processing, and output processing. Input processing contains the interface between the sensors (temperature, pressure, speed, flow, and acceleration) and the controller. Control processing contains the interface to the vehicle (telemetry information and vehicle commands) , performs high level control like thrust / mixture ratio control, and any real-time algorithms. Finally, the output processing section contains the effector control drivers (solenoids, igniters, and closed loop actuators) and receives all valve positions (RVDT and LVDT). All functional areas connect to the data interconnect busses which will be standardized types of parallel busses. Functional areas may be made up of several circuit cards, each with a separate interface to the parallel data busses.

Channels are complete with their own separate power supply and heater. Power supplies are responsible for all power for their respective channel including sensors and valves and will be electrically isolated. The heater is necessary to keep electronics from becoming cold enough to , among other things, crack solder joints or deteriorate capacitors. If enough electrical activity is present in the vehicle between missions, for example by telemetry, heaters may be eliminated.

Each of the three main functional areas will be linked to the other channel(s) via the data busses. The type and extent of redundancy management has yet to be determined. However, an up front goal will be to minimize software complexity by simplifying the channel interaction. Technological advances in VLSI should improve channel reliability.

A preliminary schematic of the controller architecture is shown in Figure 11.

2.3.1 Input Electronics

The function of the Input Electronic module is to condition and convert engine sensor data to digital data for processing. Data to be measured includes temperatures, pressures, speeds, flows and acceleration.

For cryogenic temperature measurements, RTD's are best suited because the signal output levels are higher. A constant current supply will provide an accurate reference with the voltage drop across the RTD being directly proportional to resistance. For hot gas temperature measurement, thermocouples may be used because of their inherent structural ruggedness. Use of thermocouples will require additional circuitry to amplify the low level signals and provide ice point referencing.

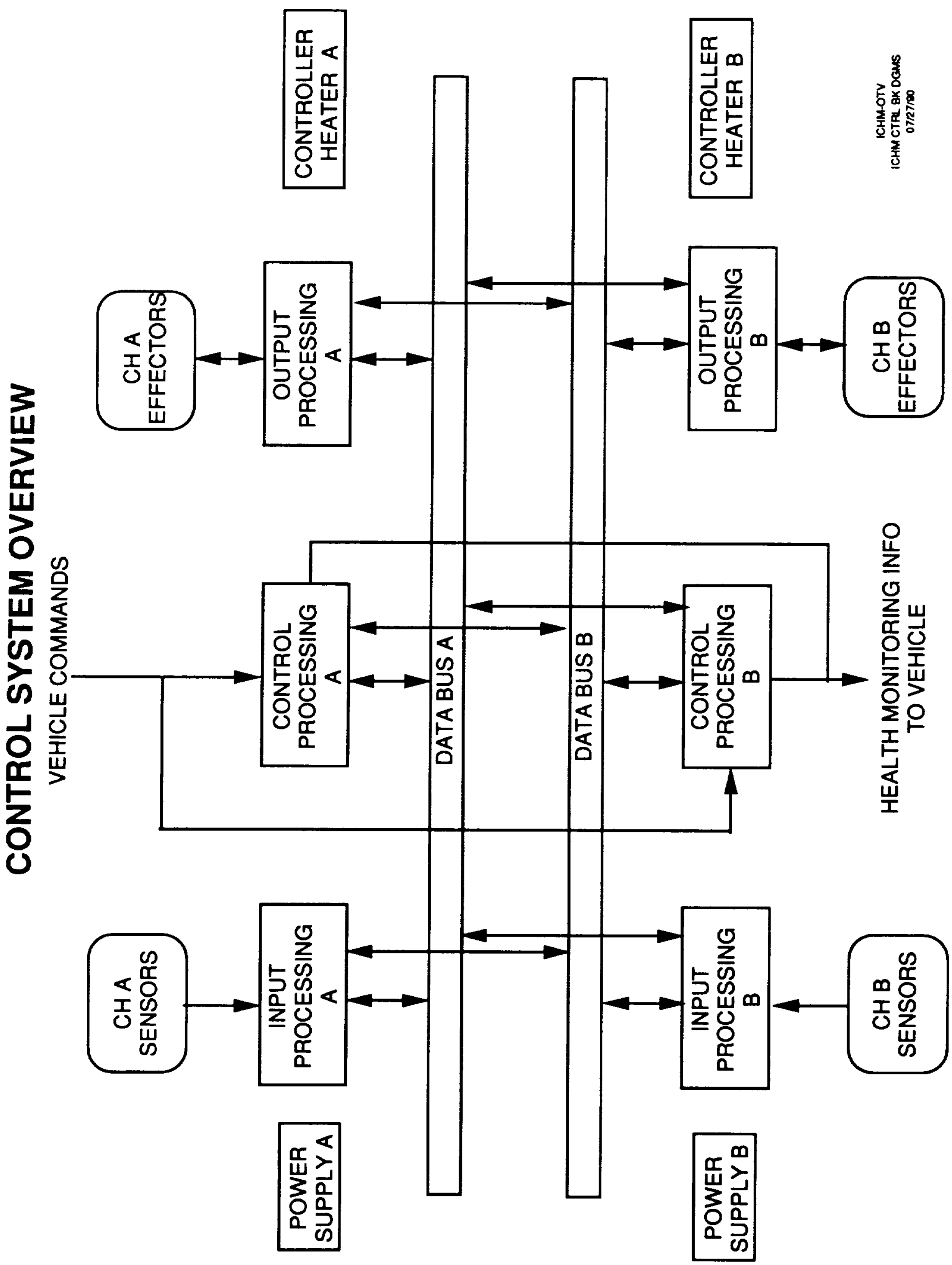

CONTROL SYSTEM OVERVIEW
VEHICLE COMMANDS
CH A SENSORS
INPUT PROCESSING A
CONTROL PROCESSING A
OUTPUT PROCESSING A
CH A EFFECTORS
POWER SUPPLY A
CONTROLLER HEATER A
DATA BUS A
DATA BUS B
POWER SUPPLY B
INPUT PROCESSING B
CONTROL PROCESSING B
OUTPUT PROCESSING B
CONTROLLER HEATER B
CH B SENSORS
CH B EFFECTORS
HEALTH MONITORING INFO TO VEHICLE
ICHM-OTV
ICHM CTRL BK DGMS
07/27/90

Figure 11

Pressure sensors require an accurate voltage reference from the Input Electronics and provide a differential bridge output. The output of the bridge is filtered and amplified and converted to a digital value for scaling in the Input Electronics Micro-controller (IEMC).

Speed and flow processing are handled in a similar manner. An EMF generated by a rotating magnetic field is picked up in a coil and the period of the generated waveform is measured using a time measurement counter. A zero crossing detector is employed to determine beginning and ending of a measurement period.

Signal Conditioning will consist of passive input filters on all inputs to reject EMI followed by a low pass filter for anti-aliasing and buffering where required. Temperature and pressure data together with any other analog data will be multiplexed into a 12 bit A-D converter for conversion to digital data.

The IEMC will perform reasonableness test based on engine model data to determine the condition of the engine sensors. Scenarios considered to accommodate unreasonable sensors include; excluding that sensor from calculations and using the channel B sensor, or possibly using a "weighted sum of system health parameters" model, with weightings adjusted to compensate for lack of the unreasonable sensor value. The IEMC will also control self test of the Input Electronics to ensure the validity of all data reported to the Controller Bus. It will perform the necessary scaling of data and report it on the Controller Bus for all users, such as the Engine Controller or the Condition Monitor.

The IEMC will consist of a 32-bit processor with a fixed program memory (PROM) and static memory (RAM) for working memory. Because its operation is critical to the input electronics, the IEMC will be a self checking controller and the memory will be an error detection and correction memory. It will provide the protocol to communicate to the Controller Bus as well as do processing. The input processing block diagram is shown in Figure 12.

2.3.2 Controller Processor

The function of the Control Processor (CP) is to receive vehicle commands such as engine checkout, start, throttle or cutoff and control the engine operation. Mixture ratio and throttle control will be done in the CP using data from the input electronics and the output electronics and sending valve position commands to the output electronics. Engine data will be stored in a bulk memory during engine operation for processing after cutoff. Fifty two measurements have been

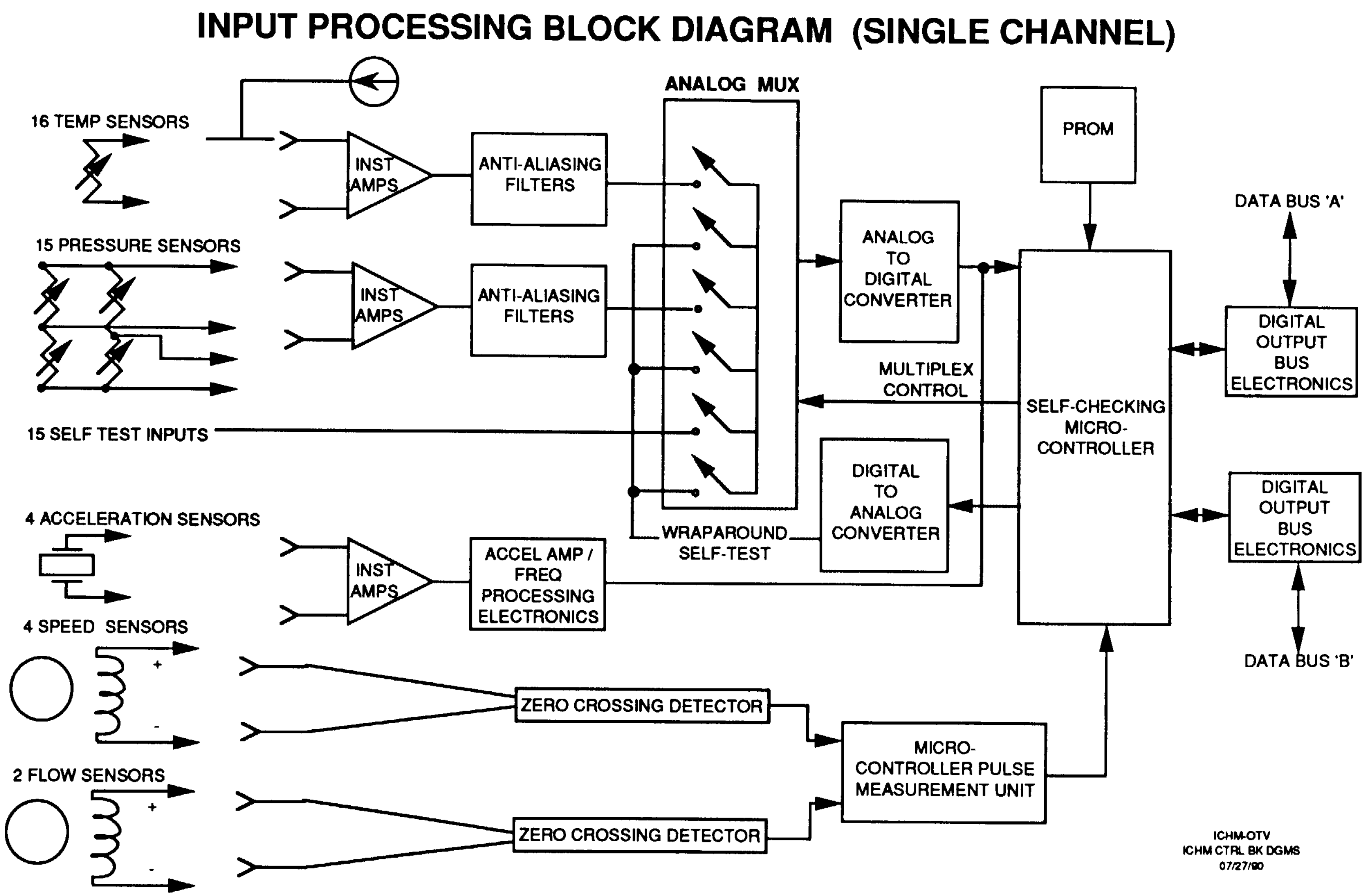

INPUT PROCESSING BLOCK DIAGRAM (SINGLE CHANNEL)
16 TEMP SENSORS
15 PRESSURE SENSORS
15 SELF TEST INPUTS
4 ACCELERATION SENSORS
4 SPEED SENSORS
2 FLOW SENSORS
INST AMPS
INST AMPS
INST AMPS
ANTI-ALIASING FILTERS
ANTI-ALIASING FILTERS
ACCEL AMP / FREQ PROCESSING ELECTRONICS
ANALOG MUX
WRAPAROUND SELF-TEST
ANALOG TO DIGITAL CONVERTER
DIGITAL TO ANALOG CONVERTER
MULTIPLEX CONTROL
PROM
SELF-CHECKING MICRO-CONTROLLER
DIGITAL OUTPUT BUS ELECTRONICS
DIGITAL OUTPUT BUS ELECTRONICS
DATA BUS 'A'
DATA BUS 'B'
ZERO CROSSING DETECTOR
ZERO CROSSING DETECTOR
MICRO-CONTROLLER PULSE MEASUREMENT UNIT
ICHM-OTV
ICHM CTRL BK DGMS
07/27/90

Figure 12

identified and fifty measurements per second will require about 1.5 Mbytes of memory for 10 minutes of engine operation. Data which requires a higher update rate, such as tracking filters or other special processing must be supported by special purpose processors to pre-process data for storage in the bulk memory. input and output electronics data received in the CP has been fully qualified and can be used without further reasonableness testing.

The CP will consist of a 32-bit processor with a fixed program memory (PROM) and static memory (RAM) for working memory. Because its operation is critical to engine control, the CP will be a self checking processor and the memory will be an error detection and correction memory.

The Controller Architecture will have two or more independent bus interfaces depending on the necessary redundancy to achieve the required reliability. Each input electronics and output electronics will be capable of communicating on each bus to provide the necessary cross strapping of engine data. The control processing block diagram is shown in Figure 13.

2.3.3 Engine Vehicle Interface and Power Supply

The elements which will be used to interface with the vehicle will include digital telemetry bus electronics, digital vehicle bus electronics, a telemetry bus, and a vehicle command bus. These elements are also shown in Figure 13.

The function of the power supply is to convert the 28 volt vehicle power to the necessary digital and analog voltages to power the controller circuits. The power supply must also contain fault monitor circuits to detect loss of input power and power supply failures.

2.3.4 Output Electronics

The function of the Output Electronics (OE) (Figure 14) unit is to receive valve position commands from the Control Processor and generate the necessary voltage and current drive required to operate the engine valves and solenoids. The OE will also monitor the valves for proper response by measurement of valve current, voltage and position. The OE will provide the command and monitoring for the ignitor modules. All solenoids and solenoid drivers will be designed to operate from 24 to 32 volts DC to make use of standard vehicle power and the solenoid drive current should be isolated from the controller power and ground.

CONTROL PROCESSING BLOCK DIAGRAM (SINGLE CHANNEL)

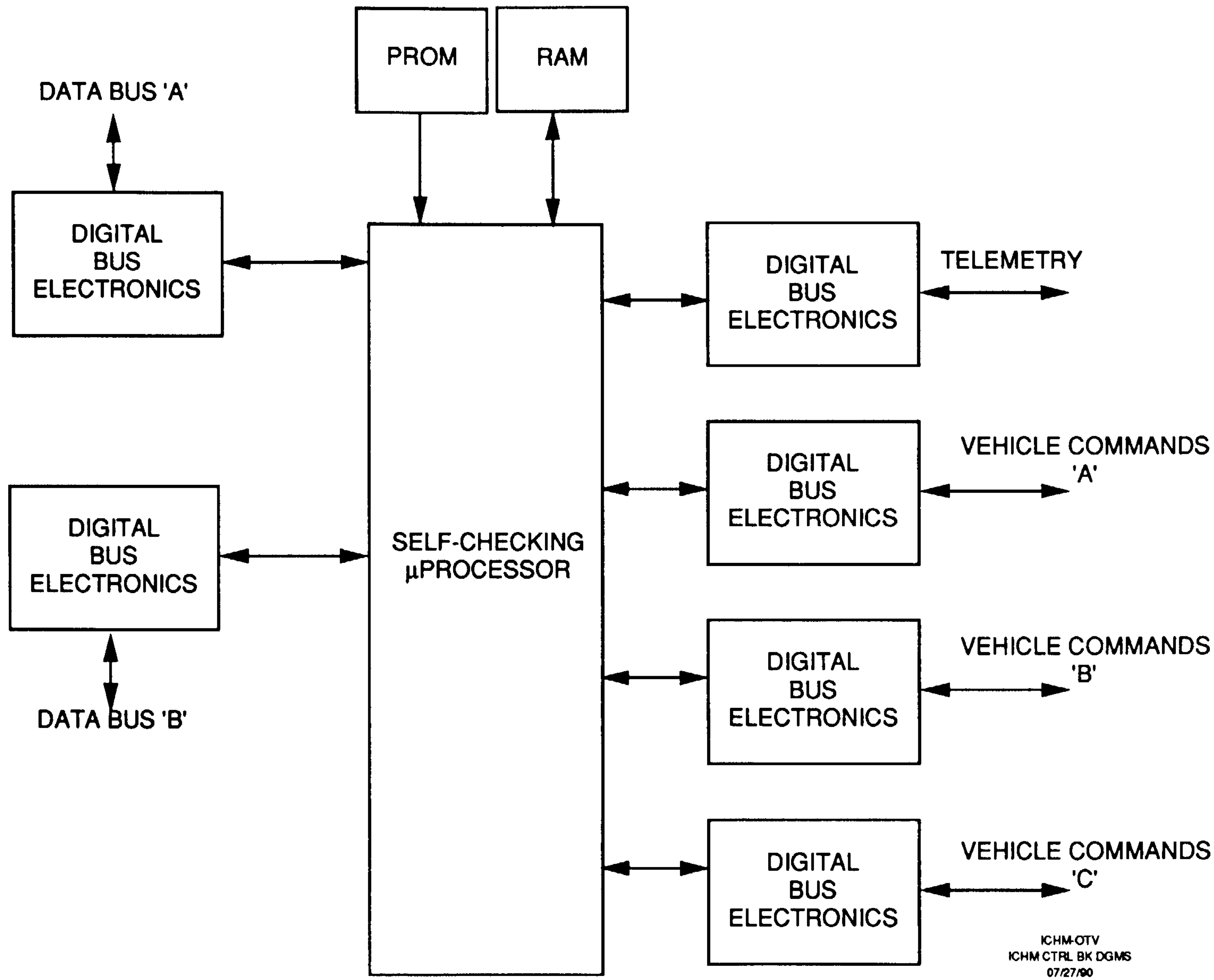


Figure 13

OUTPUT PROCESSING BLOCK DIAGRAM #1 (SINGLE CHANNEL)

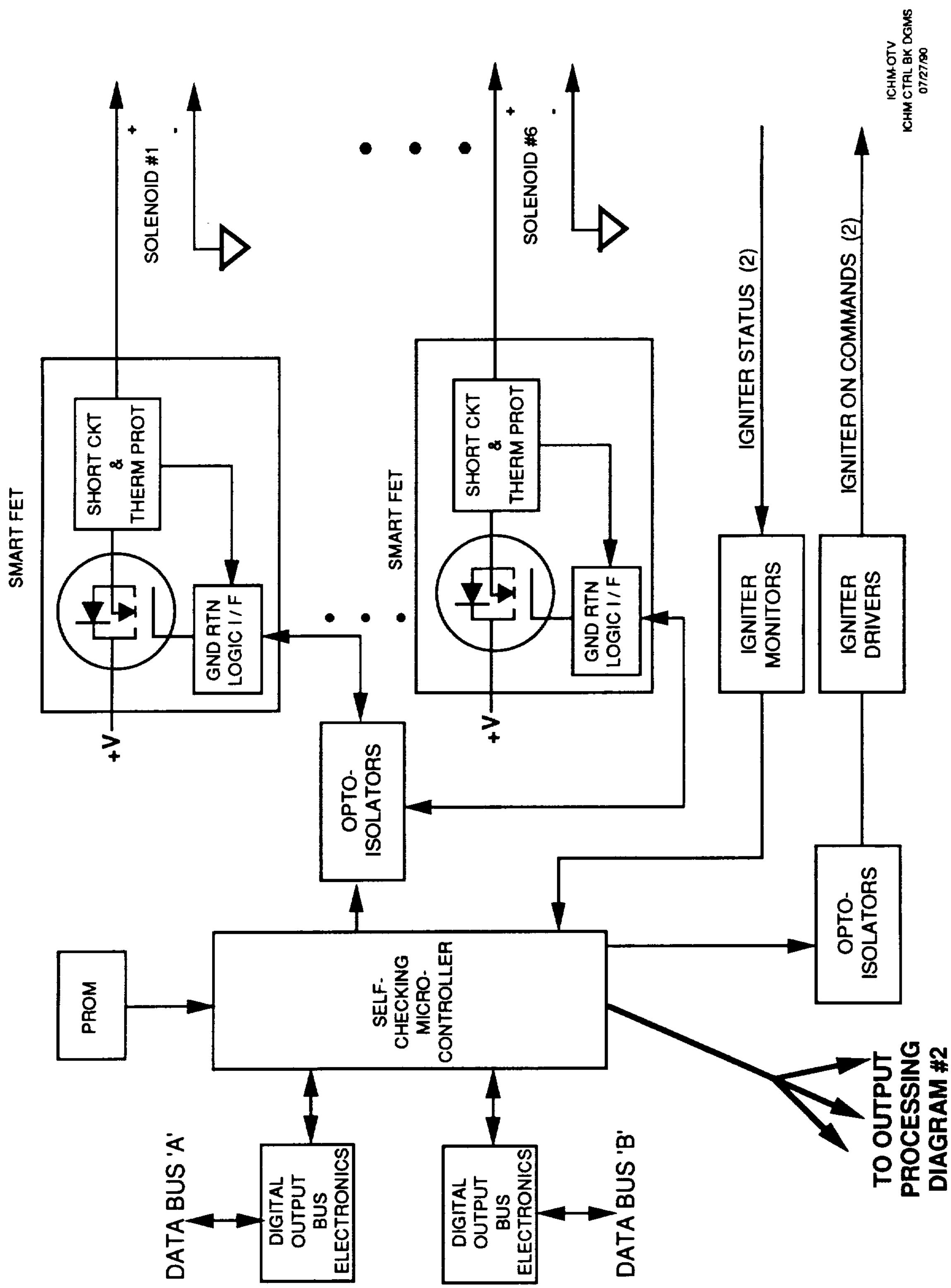


Figure 14 (part one)

OUTPUT PROCESSING BLOCK DIAGRAM #2 (SINGLE CHANNEL)

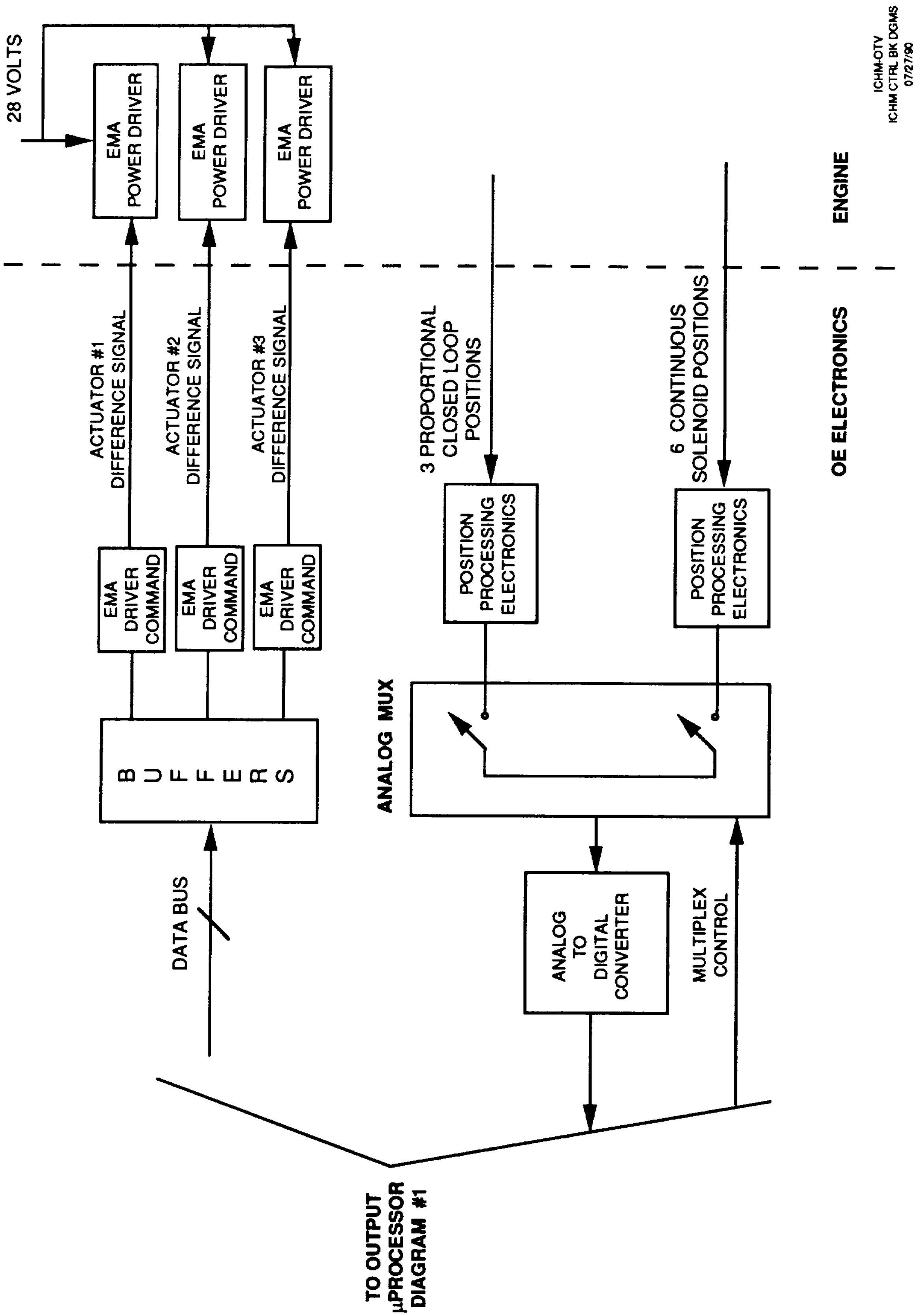


Figure 14 (part two)

Valve drivers must drive both on-off and proportional valves with high efficiency if the design goals of the control system are to be met. New valve drivers being developed for the automotive industry offer efficient operation and have built in self test features. Electromagnetic actuator drivers present a challenge both in circuit design and packaging. High efficiency amplifier design must be developed for increased efficiency.

Measurement of valve position in the past has employed RVDT'S and LVDT'S, which are not capable of better accuracy than 1% to 2%. More accuracy is required and other techniques such as radiometric RVDT'S, optical position encoders, and resolvers can provide 0.1% accuracy. Monolithic integrated circuits are available for circuit implementation of all these techniques.

Spark ignitor control and monitoring may be provided in the output electronics. To detect degradation in the spark ignitor, it will be necessary to design a monitor circuit which measures the spark energy and compares it to nominal values. A review of SSME experience will be conducted to determine the necessity of this check.

The OE functions will be controlled by an output electronics micro-controller (OEMC) with a stored memory program. Data such as valve position commands will be received in the OEMC via the Controller Bus. The OEMC will convert the command to a form required by the valve driver and verify that the valve responded. Monitoring of the valve drivers will also provide information about faulty drivers or open coils and this will be put on the bus for the health monitoring function. The OEMC will consist of a 32-bit processor with a fixed program memory (PROM) and static memory (RAM) for working memory. Because its operation is critical to the output electronics self test function the OEMC will be a self checking processor and the memory will be an error detection and correction memory.

2.4 Algorithms and Software

The ICHM software can be broken down into three categories: Engine control (includes both performance regulation and implementation of health monitoring decisions), Health Monitoring (Safety monitoring,Condition Monitoring, including Maintenance assessments), and General/ Executive functions (those which support operation of the ICHM system rather than implementing specific OTVE operating requirements and includes sensor calibration, measurement validation, and communications functions). Table 6 describe the software sub-elements organized into these categories.

CONTROL	HEALTH MONITORING
ENGINE CONTROL	**SAFETY FEATURES**
Pre-Flight Operations	Redline Monitoring
Start Sequencing	Engine Fault Emergency Shutdown
Tank Head Idle Operation	Control Failure Emergency Shutdown
Pumped Idle Operation	
Mainstage Operation	**CONDITION MONITORING**
Shutdown Sequencing	**System Condition Monitoring**
Post-Flight Operations	Pre-Flight Checkout
	Post-Flight Checkout
	In-Flight Performance Monitoring
	Data Storage
GENERAL/EXECUTIVE	**Component Condition Monitoring**
Processing Cycle Control	High-Speed Turbopump Monitoring
Exception And Interrupt Control	Data Storage
Computer Initialization	
Redundancy Management	
Command & Data Interface Control	
Input/Output Control	**PROCESSING AND DIAGNOSIS**
	Health Monitoring Data Processing
	Data Presentation
	Performance Data Processing

Table 6. ICHM Software Element Breakdown

Preliminary software functions for the minimal ICHM system are defined based on the ICHM functional requirements previously identified. In most cases, specific requirements cannot be established until the OTVE design is further defined. Therefore, the list of software functions is intended to be representative of the software expected for a minimal ICHM rather than an all inclusive baseline. In general, the development of the ICHM System algorithms and software should be straightforward, with low risk in terms of cost and schedule.

2.4.1 Engine Control

Engine control includes the code for execution of the operating sequence and closed loop control algorithms in controlling the engine through all its modes of nominal operation.

Engine safety includes the code for monitoring of engine redlines and for executing the appropriate emergency engine shutdown depending on whether and engine fault or a computer control failure had occurred.

2.4.1.1 System Condition Monitoring The system health monitoring code checks the pre-flight health and readiness of the engine and ICHM system. It also performs limited in-flight monitoring of system health. System health monitoring requirements for the minimum system include at least: continuous in-flight and pre-flight checkout; engine system readiness/health assessment; limited continuous monitoring of the ICHM system health; and transfer of monitoring data to the vehicle for storage and/or telemetry. Pre-flight checkout may be considered as "post-flight", in that any pre-flight checkout after the initial mission should recognize problems caused by the previous use.

2.4.2 Condition Monitoring

2.4.2.1 Component Condition Monitoring The component health monitoring code monitors operation of the high-speed turbopumps. In conjunction with signal processing/conditioning hardware, it extracts health indication signature information from sensor data and prepares it for data transmission. At this time, it appears that the high speed turbopumps are the leading candidates for component health monitoring. No other engine system components appear to have a significant probability of failure or major degradation during the specified service free life. The minimal system will therefore include the sensors, signal conditioning and failure/degradation software for monitoring the high-speed fuel and oxidizer turbopumps. If future analysis or test of other engine components reveal significant wear or other degradation/failure mechanism, appropriate sensors, signal processing and monitoring algorithms will be developed.

2.4.2.2 Processing and Diagnosis Maintenance decision and performance evaluation code operates in general purpose computers to process monitoring data and present it in a meaningful form for analysis by logistics and engine performance experts.

2.4.3 Executive

Real-time executive code manages the operation of all other software and provides "housekeeping" services. It includes processing cycle control, exception/interrupt handling and computer initialization. In addition the executive manages the redundancy of all control system elements, controls the command and data interface with the vehicle and and controls the sensor input and actuator output channels.

3.0 ELEMENT TECHNOLOGY READINESS FOR MINIMAL SYSTEM

ICHM functions and ICHM system elements were defined in previous subtasks. The ICHM elements which emerge from the ICHM functions fall into the following categories:

1. Sensors
2. Effectors
3. Electronics (harnessing and controller hardware)
4. Software/ Algorithms
   - A. Engine control algorithms (feedback control loops of valve position measurement/ control and fine-tuning of performance)
   - B. Safety algorithms/ advanced redline control algorithms done in real-time and used for control decisions
   - C. Condition monitoring (life prediction/ maintenance analysis/ component diagnosis) algorithms not necessarily in real-time

Items B and C, taken together constitute Health Monitoring algorithms. A, B, and C: Integrated Control and Health Monitoring algorithms. All elements together make up the ICHM system

Table 7 presents the technology readiness levels definitions, from 1 to 7, as furnished by NASA in the task work statement. Technical readiness was determined by review of the technical staff, with specific element expertise. Elements were separated into four categories: sensors, electronics, effectors, and software/ algorithms. A summary of the element categories, technologies or functional types, and element readiness levels is shown in Table 8 on the following pages.

Technology Readiness Levels: Definition

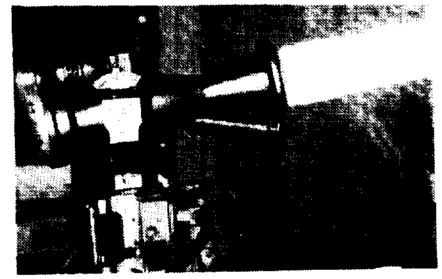
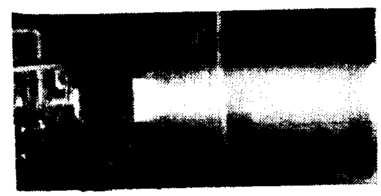
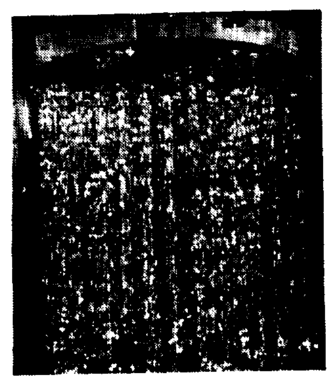
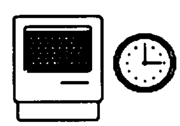
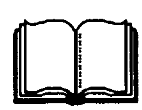
Level 7	System validation model demonstrated in space; system ready for space-based applications	 
Level 6	System validation model demonstrated in simulated environment; test of an equivalent of the final system configuration	
Level 5	Component and/or breadboard demonstrated in relevant environment	
Level 4	Component and/or breadboard demonstrated in laboratory	
Level 3	Analytical and experimental proof-of-concept for critical function and/or characteristic; conceptual design test	
Level 2	Technology concept/ application formulated; conceptual design drafted	
Level 1	Basic principles observed and reported	

TABLE 7

ICHM Elements Technology Readiness Rationale

Sensors

ELEMENT	TECHN.	RATIONALE
"Conventional" Sensors These elements include the RTD's, Fuel turbine flowmeters, variable reluctance speed sensors, and piezoelectric accelerometers.	Level 7	These elements have been used extensively on flight programs, and thereby represent technologies proven in space applications.
LOX Turbine Flowmeter	Level 6	The LOX Turbine Flowmeter was used in the early development stages of the SSME, and then was subsequently dropped from the program. It has been demonstrated on a rocket engine in a simulated (test stand) environment.
Eddy Current Sensor	Level 5	Eddy current sensors have been operated in LN2, a thermal environment which resembles liquid hydrogen. The testing has been limited to a laboratory context.
Silicon-on-Sapphire (SOS) Pressure Transducers	Level 4	Silicon-on-Sapphire (SOS) pressure transducers have not been used on any rocket engine program at Rocketdyne. The technology has been developed by several vendors whom Rocketdyne has contacted and is being considered for advanced rocket engine applications.
Silicon-on-Sapphire (SOS) Resolvers	Level 4	Resolvers based on Silicon-on-Sapphire (SOS) have been tested in the laboratory and used in industrial applications such as robotics, but have not been used on any rocket engine program at Rocketdyne. SOS technology is being developed by several vendors with whom Rocketdyne has discussed rocket engine environmental requirements.

TABLE 8 ICHM ELEMENTS TECHNOLOGY READINESS RATIONALE

ICHM Elements Technology Readiness Rationale

Effectors

ELEMENT	TECHN.	RATIONALE
Solenoid-Operated Valves: On Off Control: Gaseous Oxidizer Valve (GOV), Oxidizer Igniter valve (OIV) and Fuel Igniter Valve (FIV) Check Valves: Oxidizer Tank Check Valve (OTCV) and Fuel Tank Check Valve (FTCV) Pneumatic Failsafe Override System (inclues the pneumatic controls)	Level 7	The solenoid-operated valves, check valves and Pneumatic failsafe override system are existing flight-proven technology and are currently in service on SSME, Atlas, and Delta. Valve interface and flow capacity requirements may mandate re-sizing of existing valve designs.
Cryogenic Valves: the Main Fuel Valve (MFV)–a venturi ball valve, and the Main Oxidizer Valve (MOV)–a sector ball valve	Level 4	Development work relevant to these valves include an IR&D prototype designed for the RS-44 MOV at Rocketdyne and demonstrated in the laboratory. Additionally, RS-44 main propellant valves have been demonstrated in service on the RS-44 Integrated Control Evaluator Engine.
Servo Electric Actuators: On-off control: Main Fuel Valve Actuator (MFVA), Turbine Shutoff Valve Actuator (TSVA), and Nozzle Extender Actuator (NEA) Modulating control: Main Oxidizer Valve Actuator (MOVA), Turbine Bypass Valve Actuator (TBVA), Oxidizer Turbine Bypass Valve Actuator (OTBVA), and Thrust Vector Actuator (TVA)	Level 4	The electronic controls for these on-off and modulating actuators currently exist and are used in commercial and aerospace applications; however, these actuators and electronic control systems have not been demonstrated on a cryogenic rocket engine.

TABLE 8 ICHM ELEMENTS TECHNOLOGY READINESS RATIONALE

ICHM Elements Technology Readiness Rationale

Effectors, continued

ELEMENT	TECHN.	RATIONALE
Pneumatic Failsafe Override System	Level 2	The pneumatic activators for a failsafe EMA override system have no known successful component and/or breadboard laboratory demonstration.
Warm Gas Valves Turbine Bypass Valve TBV)—a sector ball valve, Oxidizer Turbine Bypass Valve (OTBV)—a sector ball valve, and Turbine Shutoff Valve (TSV)—a venturi ball valve	Level 2	No known successful component and/or breadboard laboratory demonstration has been conducted at the required operating pressures and temperatures. Limited wear gas seal experience exists on the J-2 engine. Shaft and seat seals need development and are critical design areas to be addressed.
Igniters Augmented Spark Igniter	Level 7	This element flies on the SSME and was flown on the J-2, and has an extensive test legacy. It has been baselined as the igniter for the ALS STME for both the gas generator igniter and main combustion chamber igniter.
Igniters Plasma Torch Igniter	Level 6	A plasma torch igniter has been used on RS-44 engine tests (15K), and has a test legacy of about 50 tests. The end diameter is about the size of one coaxial injector element. The smaller 4" faceplate of the 7.5K injector precludes the use of the l" diameter ASI, since the latter is too large to allow adequate mixing.

TABLE 8 ICHM ELEMENTS TECHNOLOGY READINESS RATIONALE

ICHM Elements Technology Readiness Rationale

Electronics

ELEMENT	TECHN.	RATIONALE
General		
Data Busses: Parallel Busses (e.g., VME, PIBUS, Multibus, Future bus, SCSI, etc) and Serial Busses (e.g., 1553, 485, 488, 422, 423, etc)	Level 4	These examples, which were considered, have seen widespread commercial use, although they have never been tested in a rocket engine environment. Unique design busses presently fly on SSME.
Power Supply	Level 5	OTV power conditioning electronics will be similar to those demonstrated on SSME controllers, but OTV-specific designs have not been laboratory tested.
Controller Heaters	Level 5	Although OTV-specific designs have not been laboratory tested, heaters are used for SSME controllers, and ICHM heaters will not be significantly different.
Redundancy Management.Elements	Level 5	Various schemes utilizing voting, self checking pairs, etc are now flying, but OTV-specific designs have not been laboratory tested.
Space qualified electronics	Level 3	Many parts desired for OTV are not on the current Qualified Parts List (QPL), and thus have not been tested.
Inputs		
Signal Conditioning Circuits: Inst amps, Anti-Aliasing Filters, Multiplexing, Zero crossing detectors, A/D converters, and RMS vibration monitoring	Level 3	The SSME controllers have similar signal conditioning circuits to those desired for OTV but the processing circuits of the latter are untested.
Input Data Processing Circuits: Microcontroller, PROM, Bus Interface	Level 3	These have seen widespread commercial use, as well as widespread military use, but are untested for OTV.
Control		
Data Processing	Level 3	These have seen widespread commercial and military use, but are untested for OTV.

TABLE 8 ICHM ELEMENTS TECHNOLOGY READINESS RATIONALE

ICHM Elements Technology Readiness Rationale

Electronics, continued

ELEMENT	TECHN.	RATIONALE
Outputs		
Data Processing	Level 3	These have seen widespread commercial and military use, but are untested for OTV.
Effector Drive Electronics	Level 3	The SSME has demonstrated electronic control for both pneumatic solenoids and hydraulic actuators, but electronic designs for electromechanical, OTV-specific effectors have not been laboratory tested.
General		
Memory	Level 2	PROM have been flown for years but may not be sufficient to satisfy the OTV requirements.
Architecture Design	Level 2	Present flight architectures are unable to meet OTV requirements. Technology concepts and/or applications have been formulated for the anticipated reliability/ redundancy requirements associated with long-term space applications.

TABLE 8 ICHM ELEMENTS TECHNOLOGY READINESS RATIONALE

ICHM Elements Technology Readiness Rationale

Software/ Algorithms

Pre-Start, Start and Cutoff Operations	Level 3	These functions will be based primarily on algorithms and software demonstrated in RS-44 engine tests, although OTVE-specific software will need to be developed. The nozzle extension function can be based upon linear actuator control technology taken from the Peacekeeper and other Rocketdyne rocket engine programs.
Mainstage and Cutoff Operations: Control: "Standard" Control Functions	Level 5	A number of control functions are relatively application-independent and, based on current work on the SSME controller, have been developed to the performance requirements anticipated for the ICHM.
Multivariable Thrust and Mixture Ratio Control	Level 2	Although developed at the concept level, OTVE may be the first specific application of these techniques.
Health Monitoring: Safety, Condition Monitoring and Signal Processing	Level 2	The safety and condition monitoring functions can based in part on algorithms and software of the SSME Block II controller and System Anomaly and Failure Detection System, but will need to be adapted to OTVE-specific needs. Other condition monitoring functions and the signal processing functions can be based upon filtering techniques and other software/ algorithms developed in ongoing turbopump health monitoring programs, but they will need to be adapted to OTVE-specific needs.
Analytical Sensor Redundancy	Level 2	Although developed at the concept level on programs such as ALS, OTVE may be the first specific application of these techniques.

TABLE 8 ICHM ELEMENTS TECHNOLOGY READINESS RATIONALE

ICHM Elements Technology Readiness Rationale

Software/ Algorithms, continued

Post Flight Processing: Engine status and Performance Analysis Software	Level 2	This software has been established and used on the SSME program in test data reduction and processing operations, but no OTVE-specific software has been established.
Off-line Health Monitoring Functions: Trend analysis, Health Assessment and Maintenance Recommentation	Level 2	At the concept level, these functions are relatively well-developed in general but have not been implemented on specific programs. OTVE may be the first application of these techniques.
General Functions: The General Functions support operation of the ICHM system , e.g., sensor calibration, measurement validation and executive functions, as well as communications functions, rather than implementing specific OTVE operating requirements	Level 5	The sensor calibration, measurement validation and executive functions can be based upon SSME Block II controller development, now at level 6. The communications functions will be implemented using space-proven MIL STD 1553B technology, Space Shuttle 1MHz serial communications or other proven technologies.

TABLE 8 ICHM ELEMENTS TECHNOLOGY READINESS RATIONALE

4.0 ESTIMATE REMAINING DEVELOPMENT COSTS FOR MINIMAL SYSTEM

Cost estimates were developed based on similar component or system development efforts. A summary of the estimating results is presented in Table 9. A brief basis of estimate is stated for each category of ICHM elements, followed by general assumptions or detailed estimating guidelines used in the respective estimates. These estimates are considered accurate to +/- 20%. An important underlying assumption is based on discussions with NASA-LeRC; that is that the level 6 validation testing engine/test stand support will be provided by NASA. This means that the Rocketdyne level 6 efforts encompass required on-site support to testing, analysis, and actions based on results of that testing. No Rocketdyne labor is estimated for running the engine in the test stand.

Controller Electronics Hardware

The controller and associated electronics were based on the SSME controller, a full authority digital rocket engine controller, which is the closest existing similar hardware program available. The entire list of non-recurring tasks portion of the basis of estimate index for the SSME Controller Block II proposal was examined and complexity factors were applied to extrapolate ICHM controller electronics estimates. Additionally a set of design ground rules was established which are presented in Appendix 1, and general assumptions were made. The electronics labor cost estimate is about $23M, and related hardware is $3M. This portion of the effort is one requiring the longest development schedule, 60 months.

General Assumptions

1. Utilize a standardized bus such as, VME, MULTIBUS, Future Bus, 1553
2. Utilize a standardized single board computer with integrated bus interfaces. The design will be brought up to a space-rated qualification.
3. Extensively use hybrids or VLSI to reduce size and weight.
4. Assume the same close technical and cost control by NASA as done during the development efforts on SSME Block I, Block II controllers.

ELEMENT CATEGORY	MANHOURS	LABOR COST	HARDWARE	TOTAL	DURATION-MONTHS
SENSORS	3710	$241,150	$236,000	$477,150	54
ELECTRONICS	354160	$23,020,400	$3,016,000	$26,036,400	60
EFFECTORS (INCL VALVES)	117344	$7,627,360	$6,593,000	$14,220,360	48
SOFTWARE	86396	$5,615,740		$5,615,740	60
				GRAND TOTAL	
				$46,349,650	

TABLE 9-OTV-ICHM COST ESTIMATE SUMMARY

Sensors

Sensors development cost estimates were based several program efforts. These include the Peacekeeper Stage IV, the SSME TTBE and Kinetic Energy Weapons programs. For each sensor selection considered, the program with the most up to date applicable cost data was used as a cost basis. A summary of the sensor cost estimates is presented in Table 10.

Sensor Estimating Guidelines

The basis for bringing a sensor to technology readiness level 5 involves qualification. This proves the sensor design in a simulated environment. This activity would require 6 manmonths of effort per sensor, over a duration of 9 months.
To get to level 6 certification from level 5 requires proving the design in a test stand green run. Going to level 6 assumes engine availability for 17 tests at 300 seconds each. Certification time is 5000 seconds. To recertify a currently certified sensor to a new engine requires manpower of 510 hours (30 hours per test for 17 tests). The adaptation of a level 7 sensor to the target application requires 20 hours per sensor.

Effectors

The valve actuator estimates were based on actual hardware development experience in similar technology applications (eg electromechanical or pneumatic driven). The nozzle extension and gimbal actuators estimates were based on engineering judgement, experience, and operational requirement interpretation. The igniter estimates were based on applications in similar-sized injectors from recent and ongoing hardware development programs. The Space Transportation Main Engine (STME) gas generator (adapted from the SSME program) is used as the basis for the augmented spark ignitor, and the subscale liquid oxygen/hydrocarbon propellant injector is used as the basis for the plasma torch ignitor. A summary of the effector cost estimates is presented in Table 11.

Effector Estimating Guidelines

Valves: The philosophy to this approach is to design the valves with the eventual flight application in mind. Granted, a flightweight valve is not required in a Focused Test Bed environment, but overall program cost (to get to the ultimate flight article) are significantly reduced by eliminating a second design iteration to go from a heavy, large envelope breadboard valve to the flight-sized

ELEMENT CATEGORY	TECHNOLOGY/TYPE	READINESS LEVEL	MANHOURS	QUANTITY	UNIT COST	MATERIAL	DURATION, MONTHS
SENSORS						0	
	SILICON ON SAPPHIRE/PRESSURE TRANSDUCER	4	1040	15	$6,000	$90,000	12
	RTD/TEMPERATURE MEASUREMENT	7	20	15	$4,000	$60,000	2
	TURBINE/FLOWMETER (FUEL)	7	20	1	$9,000	$9,000	2
	TURBINE/FLOWMETER (OXIDIZER)	6	510	1	$9,000	$9,000	6
	VARIABLE RELUCTANCE/SPEED	7	20	2	$3,000	$6,000	2
	RESOLVER/POSITION	4	1040	4	$3,000	$12,000	12
	EDDY CURRENT/POSITION	5	1040	6	$7,000	$42,000	9
	PIEZOELECTRIC/ACCELEROMETER	7	20	4	$2,000	$8,000	2
	LABOR COSTS	$241,150	3710			$236,000	**$477,150**

TABLE 10-ICHM Sensor Cost Estimate

ELEMENT CATEGORY	TECHNOLOGY/TYPE	READINESS LEVEL	MANHOURS	QUANTITY	UNIT COST	MATERIAL	DURATION, MO
CRYOGENIC VALVES	VENTURI BALL VALVE/MAIN FUEL VALVE	4		1	$35,000	$35,000	
	SECTOR BALL VALVE/MAIN OXIDIZER VALVE	4		1	$35,000	$35,000	
WARM GAS VALVES	SECTOR BALL VALVE/TURBINE BYPASS VALVE	2		1	$35,000	$35,000	
	SECTOR BALL VALVE/OXIDIZER TURBINE BYPASS VALVE	2		1	$35,000	$35,000	
	VENTURI BALL VALVE/TURBINE SHUTOFF VALVE	2		1	$35,000	$35,000	
SERVO ELECTRIC ACTUATORS	ON-OFF CONTROL/MAIN FUEL VALVE ACTUATOR	4		1	$5,000	$5,000	
	MODULATING CONTROL/MAIN OXIDIZER VALVE ACTUATOR	4		1	$10,000	$10,000	
	MODULATING CONTROL/TURBINE BYPASS VALVE ACTUATOR	4		1	$10,000	$10,000	
	MODULATING CONTROL/OXIDIZER TURBINE BYPASS VALVE ACTUATOR	4		1	$10,000	$10,000	
	ON-OFF CONTROL/TURBINE SHUTOFF VALVE ACTUATOR	4		1	$5,000	$5,000	
	ON-OFF CONTROL/NOZZLE EXTENDER ACTUATOR	4		1	$10,000	$10,000	
	MODULATING CONTROL/THRUST VECTOR ACTUATOR	4		1	$10,000	$10,000	
SOLENOID-OPERATED VALVES	ON-OFF CONTROL/GASEOUS OXIDIZER VALVE	7		1	$15,000	$15,000	
	ON-OFF CONTROL/ OXIDIZER IGNITER VALVE	7		1	$15,000	$15,000	
	ON-OFF CONTROL/FUEL IGNITER VALVE	7		1	$15,000	$15,000	
CHECK VALVES	OXIDIZER TANK CHECK VALVE	7		1	$1,000	$1,000	
	FUEL TANK CHECK VALVE	7		1	$1,000	$1,000	
PNEUMATIC FAILSAFE OVERRIDE	PNEUMATIC CONTROLS FOR FAILSAFE OVERRIDE SYSTEM	7		1	$42,000	$42,000	
	PNEUMATIC ACTUATORS FOR FAILSAFE OVERRIDE SYSTEM	2		1	$64,000	$64,000	
	NOZZLE EXTENDER ACTUATORS	7		2	$25,000	$50,000	
	GIMBAL ACTUATORS	7		2	$25,000	$50,000	
	SUM, VALVE DESIGN, DEVELOPMENT & TESTING HOURS		45344				48
	SUM, ACTUATOR DESIGN, DEVELOPMENT & TESTING SUPPORT HOURS		66000			$6,000,000	48
IGNITERS	AUGMENTED SPARK IGNITERS	7	2000	3	$15,000	$45,000	
	ALTERNATE PLASMA TORCH IGNITERS	6	4000	3	$20,000	$60,000	
	LABOR COST	$7,627,360	117344			$6,593,000	$14,220,360

TABLE 11-ICHM Effector Cost Estimate

article. This approach did, however, consider applying an "experimental" hardware method (7R drawings, Category VII) to the design process. This facilitates the development process by requiring substantially fewer reviews and signatures, and far less processing, for the implementation of iterative design changes through the development process. 7R drawings are engineering drawings used for experimental hardware. They do not undergo full configuration management and control, and do not go through the formal engineering release process like 9R (Category II) drawings do. A more detailed explanation of these drawing types is found in Appendix II, Engineering Drawings, Categories and Uses. This experimental, 7R drawing estimating basis is appropriate and was adopted as a result of discussions with LeRC during the course of this program. The sum estimate of valve design and design verification testing (DVT) labor for all valves and the pneumatic control assembly is 45,344 hours.

Actuators: This cost is based on the SSME actuator evolution from conceptual design to development test for a deliverable product. In this case an outside vendor designed, developed and tested the actuators, and Rocketdyne provided support. The team worked on a man-rated design that met the fail-op/fail safe requirements which are found on the ICHM program. Although the subject SSME actuator is hydraulic, hydraulic actuator technology at the start of that development is comparable with today's commercially existing EMA technology. The estimated cost was $6M for the ICHM effort, reflecting the reduced complexity of design (and related design verification testing) change implementation realized when going from NASA development to NASA experimental hardware production. The $6M is treated as hardware for costing purposes, since it is a commodity purchased out-of-house. The estimate of Rocketdyne actuator design and design verification testing (DVT) "support to vendor" labor for actuators is 66,000 hours. Both the valve and the actuator efforts are estimated to require 48 months of schedule.

Ignitors: Ignitor costs considered a parallel effort of preparing two styles of ignitors for the target ICHM application. This is considered since 2 different thrust levels are being considered for the OTVE implementation, and different styles of ignitors are better suited for each respective thrust level. A 20Klb configuration would accommodate an augmented spark ignitor (ASI) configuration, where the smaller injector faceplate and injector element diameters of the 7.5Klb OTVE would require a plasma torch ignitor. For either style ignitor, a three unit basis was used for material estimating, two for the main combustion chamber redundant ignitor configuration, and one spare. For the ASI, $15,000 each was used for material cost, plus 2000 hours to adapt the current level 7 design. For the plasma torch ignitor, material basis was $20,000 each, plus 4000 hours for adapting the current level 6 article design. The time duration required for either ignitor development is 12 months.

Software/Algorithms

These development cost estimates were based on complexity factors and ICHM adaptation effort applied to the SSME controller software. Software functions were defined in terms of software lines of code. This was translated to cost using an "hours per line of code" conversion factor on the "adapted, complexity-factored" lines of code for the sum of ICHM software functions.

Software Estimating Guidelines

This activity started with considering how many hours per software line of code (SLOC), are required to adapt similar code to level six, where the existing code is at a specific technology readiness level. The assumption used is that the software code should be refined enough for "expensive asset" end uses since the Focused Testbed Engine and test stand for ICHM application would be of substantial value. Software development methods (degree of quality assurance, testing, etc.) for the expensive asset category are those which are currently followed for propulsion systems used for launching expensive satellites, in un-manned spacecraft. Other types of end uses are non-flight, and manned flight.

Hours to adapt each SLOC to ICHM level 6

expensive asset application	current level of similar function
4.0	7
5.4	6
5.6	5
5.8	4
6.0	3
6.2	2
6.4	1

A complexity factor (typically between 1.0 and 1.4), was developed relative to the SSME functions, to quantify the relative degree of complexity in implementing similar ICHM functions. The hours/SLOC was multiplied by this complexity factor, along with the number of lines of code in a given function.

Thus: (Hours/SLOC for adapting a function to ICHM to level 6) x (complexity factor) x (number of lines in a function) = hours of labor per software function. The results of using this method on each function were summed to give the total estimated hours of labor, which is 86396 hours.

CONCLUSION

An ICHM system was conceived for use on a 20Klb thrust baseline OTV engine. The approach to this conception was to provide the requisite ICHM functions in a configuration with minimal elements and applying current technologies wherever possible.

This report described how the ICHM functions were derived from flowing down requirements from the statement of work and other OTV engine or ICHM documents. The elements of an ICHM were identified and listed, and these elements were described in sufficient detail to allow estimation of their technology readiness levels.

The ICHM elements were assessed in terms of technology readiness level, and supporting rationale for these assessments was presented.

The remaining development cost for development of the minimal ICHM system to technology readiness level 6 were estimated. The estimates were based on similar program activities and are within an accuracy range of plus or minus 20%. The cost estimates cover what is needed to prepare an ICHM system for use on a focussed test bed for an expander cycle engine, excluding support to the actual test bed firings.

The system which was described represents a minimal system, with potential for future growth in both capability and incorporation of advances. The estimated cost represents a reasonable amount of resources which could be applied to allow a demonstration of the ICHM by the year 2000.

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APPENDIX 1, ELECTRONICS DESIGN GROUND RULES

Controller Electronics Hardware Design Groundrules

1. Use hybrids to reduce size of temperature and pressure circuits.
    - A. Programmable constant current supplier
    - B. Electronic aliasing filters
2. Use .050" pin to pin spacing - not flown in space yet.
3. Use ramp clamps to get heat to side rails.
    - A. Use electrical heaters
    - B. Use electrical coolers if required
4. Assume SSME card for pricing.

CONTROLLER CIRCUIT CARD DIVISIONS

INPUT PROCESSING CARDS

IE1/IE2/IE3	8 temperature channels (programmable)
	8 pressure sensor channels
	8 self test inputs
IE4	6 vibration processor channels
IE5	8 speed/flow measurement units

CONTROL PROCESSOR CARDS

CP1	Vehicle interfaces
CP2	Control
CP3	Mass memory (Maintenance monitoring)

OUTPUT PROCESSING CARDS

OE1	Position feedback and EMA command drivers
OE2/OE3	4 solenoid and 2 igniter drivers

POWER SUPPLY CARDS

PS1 Similar to A2 of SSME Block II PS (Regulator)
PS2 Similar to A4 of SSME Block II PS (Transformer)
PS3 Similar to A4 of SSME Block II PS (Power)
PS4 Voltage monitor and Thermal control (1/2 VM1 card in SSME Block II)

MODEL

M1 Processing card for analytical redundancy model

GENERAL OTV CONTROLLER DESIGN TASKS

1. Requirements Definition
   - A. Write a hardware specification
   - B. Write a software specification

2. System Design
   - A. Set architecture
   - B. Functional allocation
   - C. Implementation approach
     1. Select logic family, self checking microprocessors, data busses
     2. Memory study (nonvolitale memory)
   - D. Electrical Design
   - E. Mechanical Design
     1. Thermal
     2. Packaging

3. Brassboard (2) Use prototype cards

4. Prototype

5. Qualification Unit - perform testing in simulated flight environment

6. Software Development

A. Design IE1,2,3,4,5,CP1,2,3,OE1,2,3,M1
B. Test

CIRCUIT CARD DESCRIPTIONS AND DESIGN TASKS

INPUT ELECTRONICS

IE1/IE2/IE3 - Temperature/pressure card - Has temperature and pressure interface circuits with A/D, microcontroller, analog multiplexer, and the bus interface electronics. The interface circuits include hybrid designs.

IE4 Vibration processor card - Has accelerometer input interface circuits, tracking filters, microcontroller and bus interface circuits.

IE5 Speed/flow card - Has the speed/flow interface circuits, time measurement circuits, and bus interface electronics. Time measurement units may be microcontroller based.

CONTROL ELECTRONICS

CP1 Vehicle interface card - Has 3 serial to parallel interfaces for redundant communication between the vehicle and control processor.

CP2 Control processor card - Has the main self-checking control processor including program memory and internal bus electronics.

CP3 Mass memory card - Has the volatile memory - that is sized to record all measurements during engine operation for processing after engine cutoff.

OUTPUT ELECTRONICS

OE1 Position control card - Has a microcontroller, memory, position measuring circuits, A/D converter for self test, analog interface drivers to EMA modules and bus electronics. The power driver circuits are to be in the EMA assembly.

OE2/OE3 Device driver card - Has microcontroller, memory, 4 smart solenoid drivers, igniter command circuit, igniter monitor circuit, and bus interface electronics.

POWER SUPPLY ELECTRONICS

PS1/PS2/PS3 Power supply cards - Will convert input power to logic and analog voltages required to power controller. Does not power EMA's or regulate solenoid or igniter power.

PS4 Voltage monitor and Thermal card - Monitors power supply performance, watchdog timers, and the thermal regulator for controlling heater/cooler.

MODEL

M! Model card - Contains processor, memory, bus interface, reads all measurements, and predicts performance in real time as an analytical redundancy channel.

Design Tasks for all cards listed :

1. Design to specification
2. Preliminary design - Review
3. Breadboarding of critical circuits
4. Card testing specification
5. Prototype card testing
6. Integration into brassboard
7. Final design release
8. Fabricate cards

TABLE I DRAWINGS AND HARDWARE - CATEGORIES AND USES

CATEGORY	DRAWING AND PART NUMBERS	ORDER PTS. BY	CHANGE PTS. BY	QA INSP. REQMTS.	SQUAWK DISPOS. BY	CHANGE DRAWING BY
I CONCEPTUAL (LEVEL I PER MIL-D-1000A)	AP OR LE PREFIX TO NUMBER SUPPLIER PT. NO. (ALSO SEE CAT VII) A	EWR & 25-R E	EWR & 25-R (REDLINE MARK-UP OF PRINT) B	AS SPECIFIED BY EWR & 25-R E	ENGINEER SIGN-OFF	DWG REVISION
II DEVELOPMENTAL (LEVEL I PER MIL-D-1000A)	9R123456-XXX 9RE1234-XX (OR) SUPPLIER PT. NO. A	EO OR PER PLAN	EO & DWG. REVISION C	PER PLAN	ENGINEER SIGN-OFF, D OR PER PLAN	EO & DWG REVISION C
III PROD. PROTOTYPE & LIMITED PROD. (LEVEL 2 PER MIL-D-1000A)	R123456-XXX RE1234-XX B	EO	EO & DWG REVISION	PRODUCTION	MATL. REVIEW BOARD	EO & DWG REVISION
IV PRODUCTION (LEVEL 3 PER MIL-D-1000A)	R123456-XXX RE1234-XX B	EO	EO & DWG REVISION	PRODUCTION	MATL. REVIEW BOARD	EO & DWG REVISION
V TEST SUPPORT	8R123456-XXX 8RE1234-XX (OR) SUPPLIER PT. NO. A	EO	EO & DWG REVISION C	PRODUCTION OR PER PLAN	ENGINEER SIGN-OFF, OR PER PLAN D	EO & DWG REVISION C
VI MOCK-UP	6R123456-XXX 6RE1234-XX (OR) SUPPLIER PT. NO. A	EO & 25-R E	EO & DWG REVISION C	PER PLAN (OR) EO OR 25-R E	ENGINEER SIGN-OFF, OR PER PLAN D	EO & DWG REVISION C
VII EXPERIMENTAL-IN-HOUSE ONLY (USE CAT II FOR DEL TO CUST)	7R123456-XXX 7RE1234-XX SUPPLIER PT. NO. A X-EO R9XXXXX	X-EO & 25-R OR PER PLAN E	X-EO, 25-R, & DWG REVISION B	PER PLAN OR AS SPECIFIED BY X-EO & 25-R	ENGINEER SIGN-OFF	X-EO & DWG REVISION

TABLE I NOTES

DWG CAT:

I Numbers assigned and controlled by Advance Projects and Laser Engineering Design functions. Hardware is used to evaluate conceptual approaches and is not normally deliverable as Rocketdyne products. Drawings and parts per II thru IV may be used, as appropriate, and parts ordered per I. Changes to these parts, inspection and squawk dispositions, and drawing changes shall be per the requirements specified for II thru IV respectively unless reidentified per I. "Releasing EO's" will be prepared by the Design function to have drawing originals microfilmed and retained in the Engineering Document Repository.

II Drawing numbers assigned and affixed by Numbers Assignment. Hardware may be deliverable for customer experimentation. Drawings and parts per III and IV may be used, as appropriate, and parts ordered per II. Changes to these parts, inspection and squawk dispositions, and drawing changes shall be per III and IV unless reidentified per II.

III Drawing numbers assigned and affixed by Numbers Assignment. Only III and IV hardware may be used in the product. GSE/AGE will normally be ordered in this Category (Level 2) and are assigned "RG" numbers per DFM 742-0001.

IV Drawing numbers assigned and affixed by Numbers Assignment. Only IV drawings and hardware are used in the product. Supplier hardware shall be "controlled" with Specification Control Drawings and Source Control Drawings.

V & VI Drawing numbers assigned and affixed by Numbers Assignment. Hardware is used to support testing/evaluation of hardware for I thru IV projects and may be deliverable for like activities by the customer. Drawings and Parts II, III, and IV may be used as components. Changes to such parts, Inspection and squawk dispositions shall be per II, III, and IV as applicable. Excluded from V are tools, fixtures, and devices for which Manufacturing, Quality Assurance, or Facilities and Industrial Engineering are responsible.

VII Drawing numbers assigned and affixed by Numbers Assignment. Drawings and hardware are not deliverable and are used by D&D functions to simulate an item for experimentation only leading to design solutions for III and IV. These drawings shall not be used to define and fabricate complete products or product components. Originating Engineers are personally responsible for providing originals to Engineering Release for recording, microfilming and retention in the Engineering Document Repository.

NOTES:

(A) Comercial/Supplier parts may be used by direct call-out for Category I, II, V, VI and VII projects. Specification Control Drawings and Source Control Drawings shall be used for III and IV projects unless specifically exempted by the contract and so stipulated in the Engineering Plan of Aciton (EPCA).

(B) Redlining of prints requires the authorizing Engineer's signature and date. This is not recommended as a general practice due to potential loss/misinterpretation of design solution definition.

(C) When authorized by the EPOA for the Program or Project, Engineering "on-the-spot" changes to drawings and parts for II and IV will be defined by EC. The EC will be signed by the Engineer and will include a statement similar to the following:

"ON-THE-SPOT CHANGE MADE TO (Enter the part number and serial number or Manufacturing Work Order Number as applicable.)"

The originating Engineer is personally responsible for providing EO originals to Engineering Release for release. Release action, distribution of copies, and attachment to drawings shall be the same as for other EO's for the project.

(D) Squawks may be dispositioned by assigned Engineers by sign-off on the work order or receiving report and, when elected by the Engineer/Project Engineer, documented by EO per (C). Requirements to document by EO or other methods of dispositioning will be established by the EPOA.

(E) R25-R-2's shall be forwarded to Date Management who will enter data and patent flysheet requirements for the order. When inspection requirements are not specified on the R25-R-2, Receiving QA verifies for identification, damage and count only.